Prospects for BSM Discoveries with Belle II@SuperKEKB

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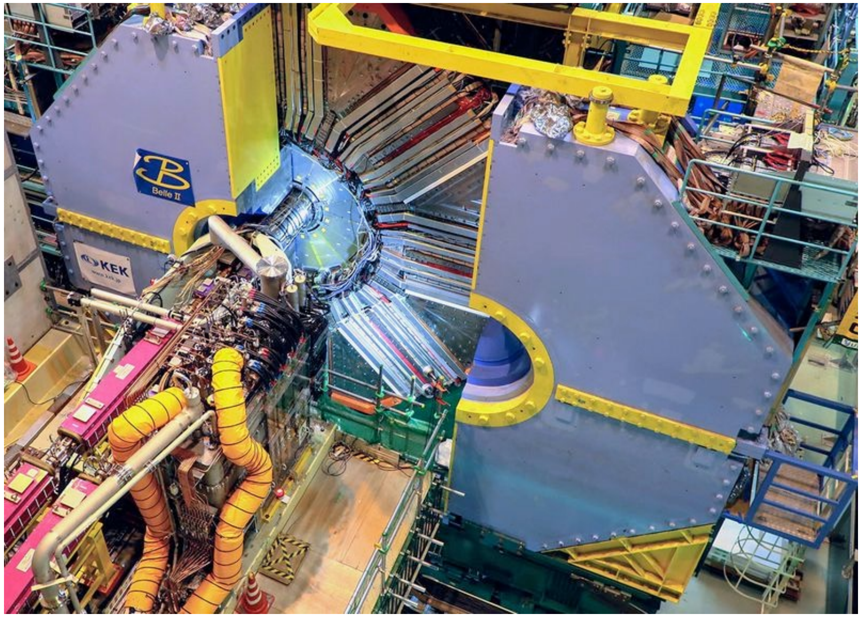
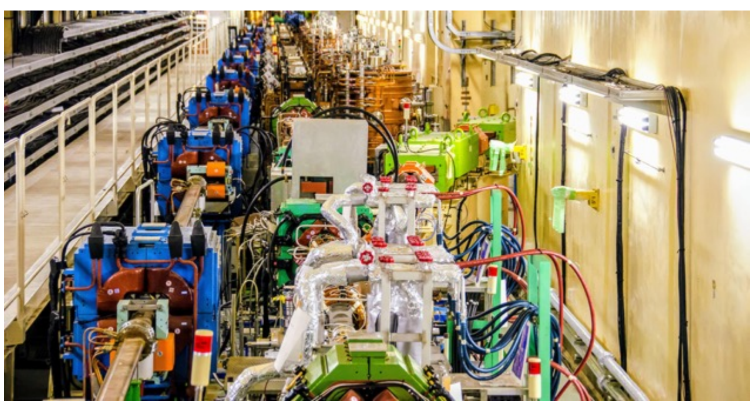
Belle II



The complex superconducting final focus is partially visible here (before closing the endcap).



Inside the SuperKEKB tunnel

Goal: Understand the significance of the recent B→K$\nu\,\bar{\nu}$ result from Belle II.

Belle II status and introduction;
How some recent Belle II results address Anomalies and *Fundamental Questions in Flavor Physics.* *(examples: Time Dependent CPV, QM, Penguins, the K π puzzle…).*

Opportunities/Prospects for *Beyond the Standard Model (BSM) discoveries at Belle II* **(What's new in 2024 and beyond ?)**

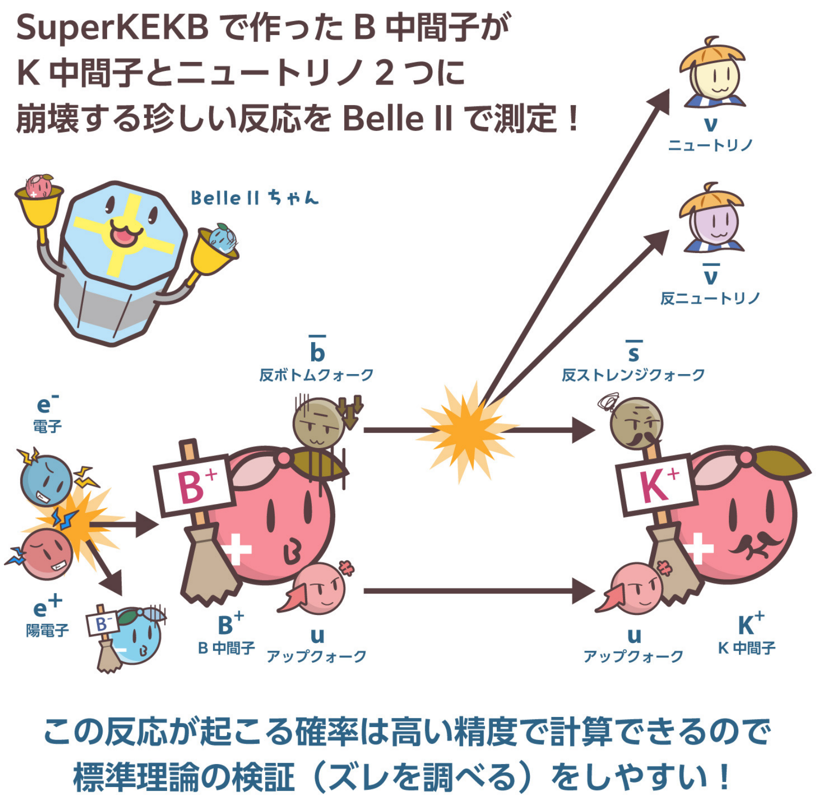
Belle II/SuperKEKB Snowmass White Papers:
https://confluence.desy.de/display/BI/Snowmass+2021

Our learning goal for this morning:

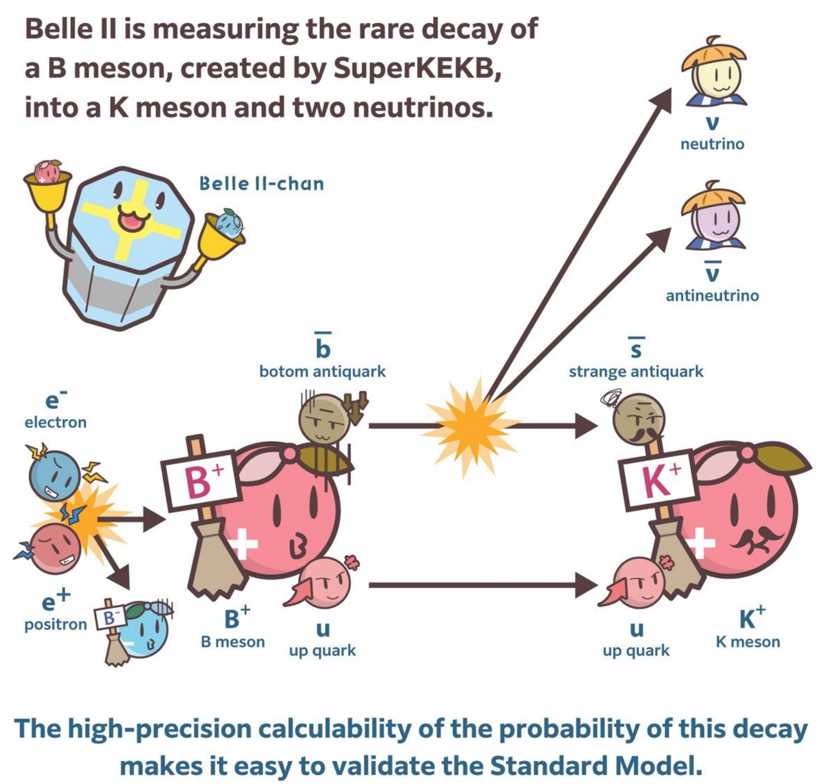
Why is the first evidence for the weak decay $B \rightarrow K\nu\bar{\nu}$ at Belle II significant?

Why is there a manga about this topic ?

How could this lead to a discovery of BSM physics ?



Japanese Original



English Translation

A b quark has charge -1/3, an s quark has charge -1/3 so this decay is a flavor changing neutral current (FCNC).

The Geography of the International Belle II collaboration

Recent additions:
Sweden, UK

Belle II
Italy:
9 institutes,
~76
members

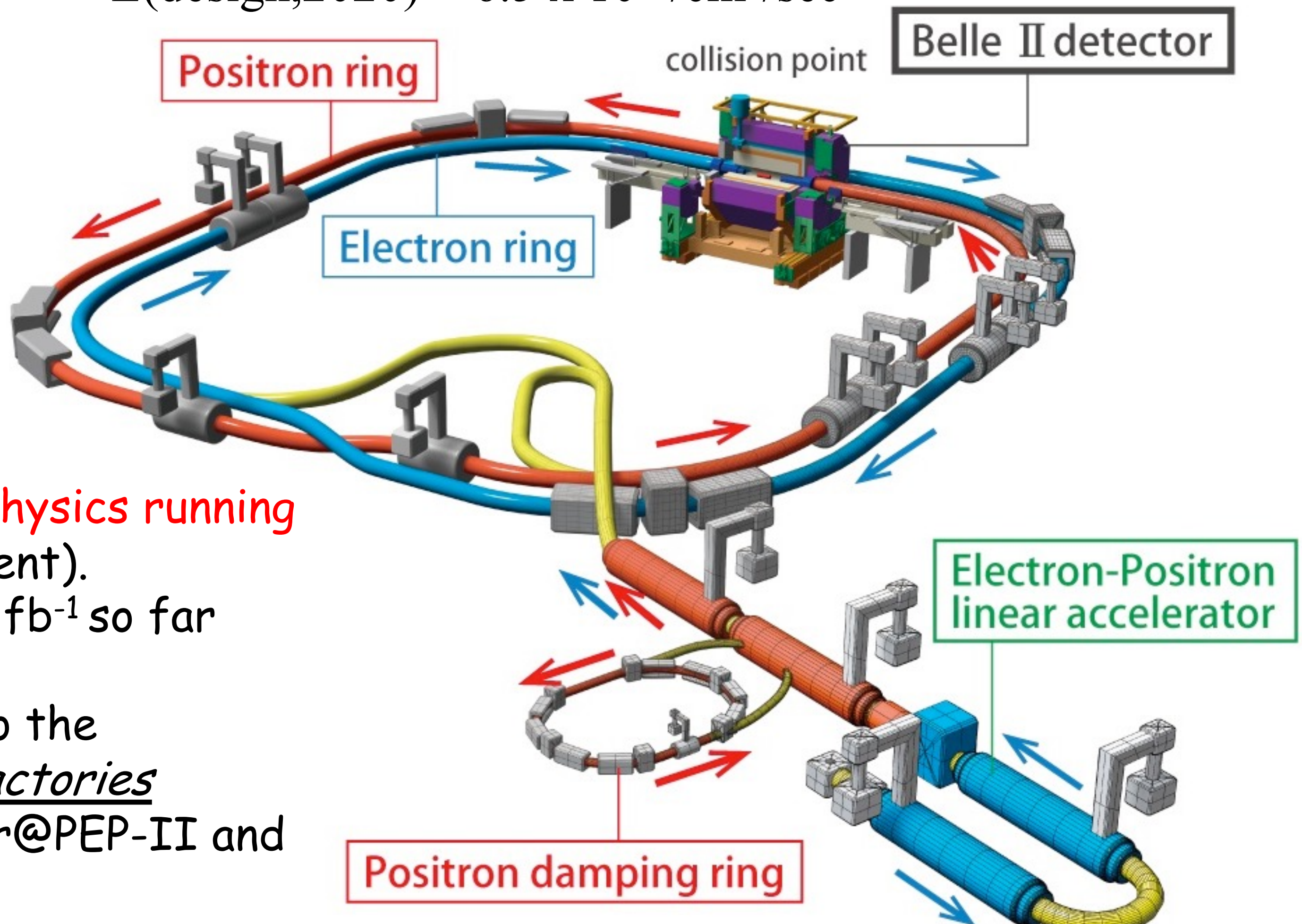
Belle II now has grown to ~1000 researchers
(~600 authors) from 28 countries/regions

Belle II is <u>unique</u> in Japan. The only comparable example is the T2K neutrino experiment at JPARC, which is also an <u>international collaboration</u>

Youth and potential: There are ~300 graduate students in the collaboration

SuperKEKB, the first new collider in particle physics since the LHC in 2008 (electron-positron (e^+e^-) rather than proton-proton (pp)). Operates on the *Upsilon(4S) resonance* with 7 GeV(e-) on 4 GeV(e+) beams.

L(design,2020) = 6.5 x $10^{35}/cm^2/sec$

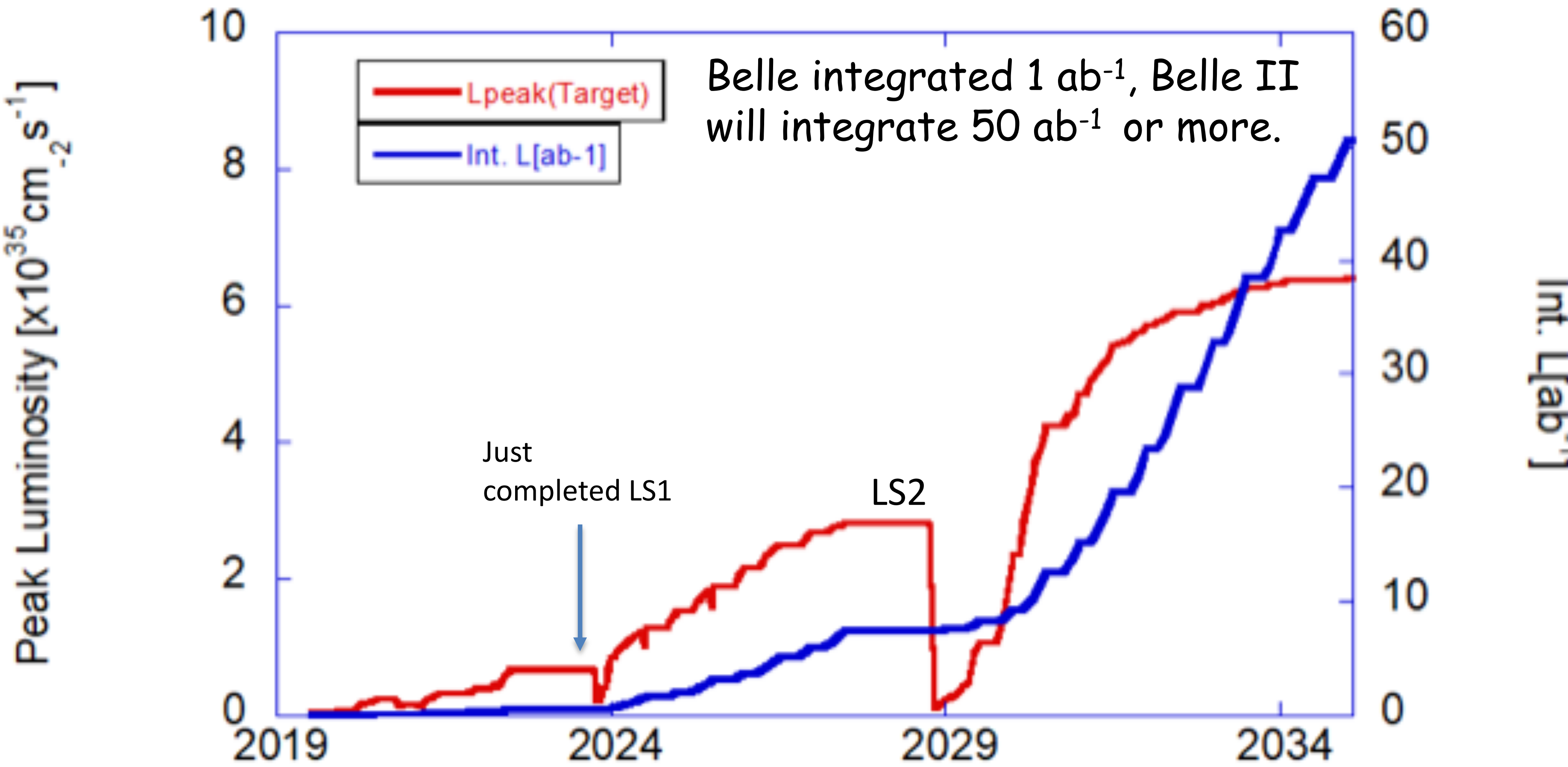


Phase 3: → Belle II Physics running
(spring 2019 to present).
Have integrated 428 fb^{-1} so far

(Dataset compared to the
First Generation B factories
(before 2010) ~BaBar@PEP-II and
~1/2 Belle@KEKB)

Accelerator innovations: nano-beams and crab waist optics (*rather than large beam currents*)

An innovative machine (a ribbon beam, 50nm high) and a plan for the next decade and beyond



Currrent beam spot is 200nm high.

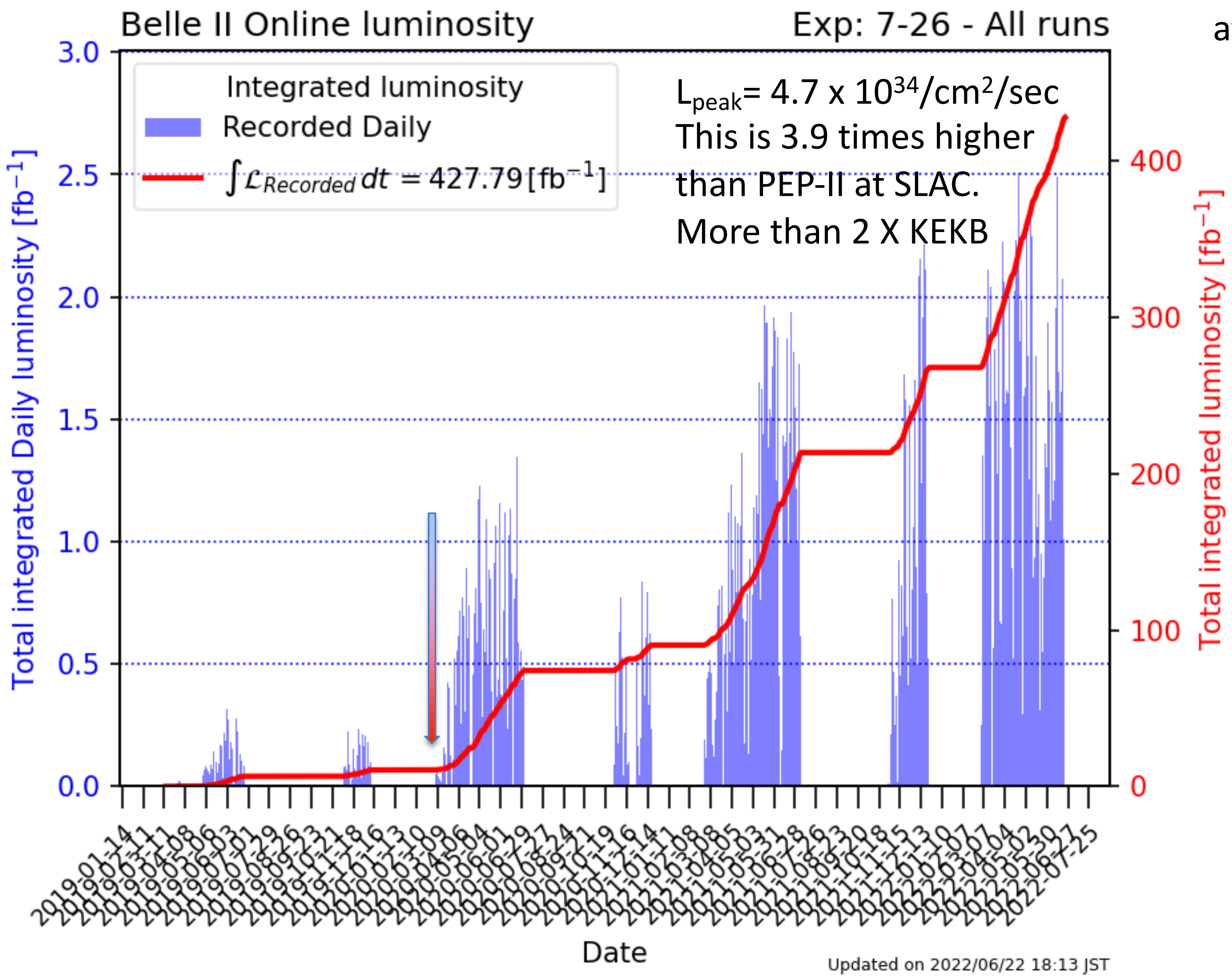
Needs international accelerator cooperation: CERN, DESY, BNL, SLAC, Cornell, ESRF, IHEP, BINP.

We now realize that SuperKEKB is a ”test bed” for FCC-ee, a 100 km circumference *electron-positron* machine planned at CERN

Ran Belle II and SuperKEKB *through the global pandemic*.

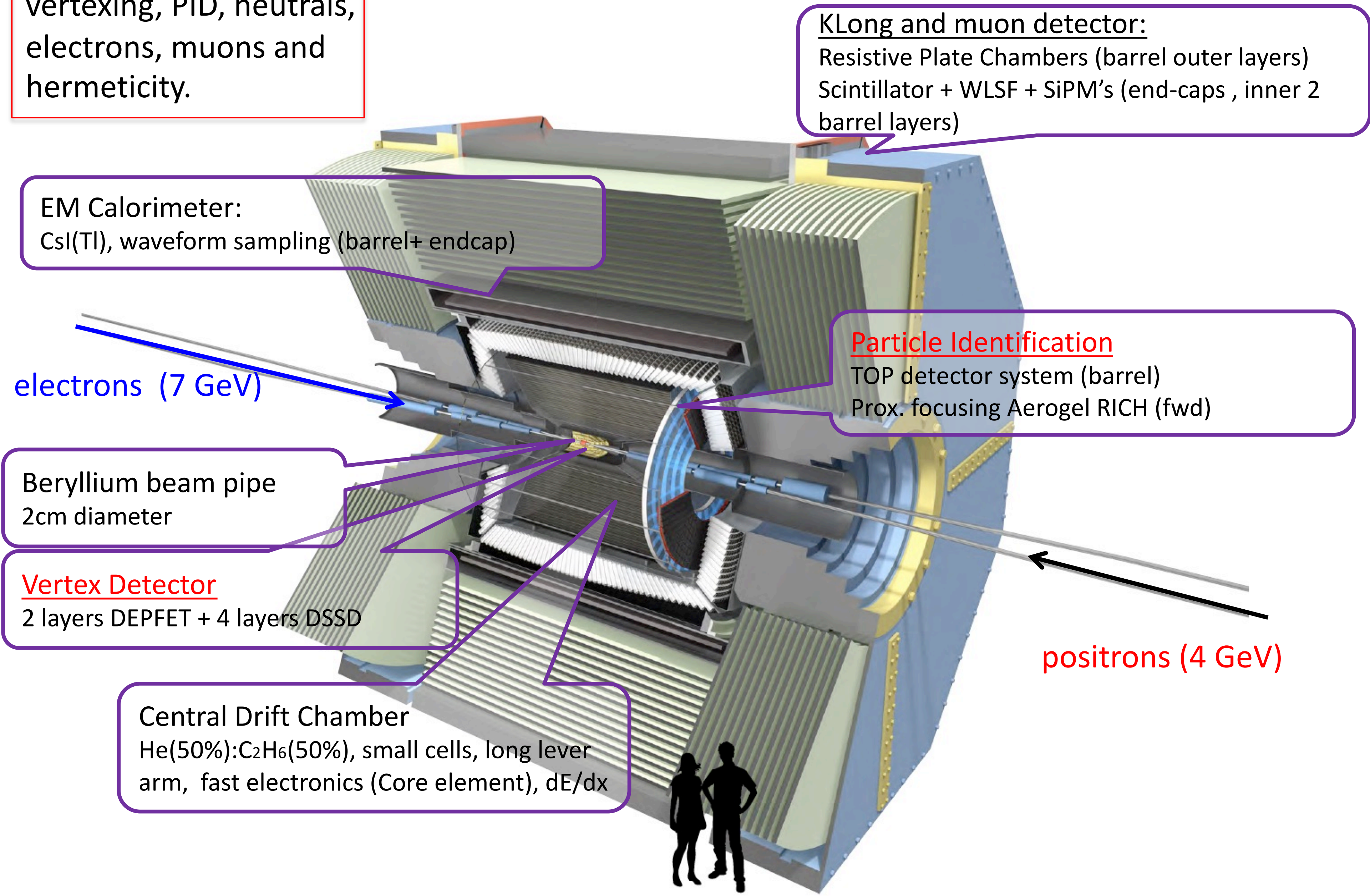
Broke many accelerator world records for luminosity.

Int(L dt)/day $=2.5\ fb^{-1}$ $\gg 0.9\ fb^{-1}$/day at PEP-II



The Belle II Detector

A multipurpose HEP spectrometer with vertexing, PID, neutrals, electrons, muons and hermeticity.

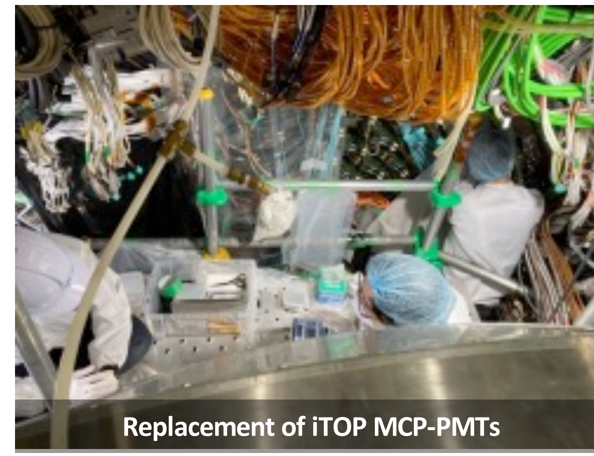


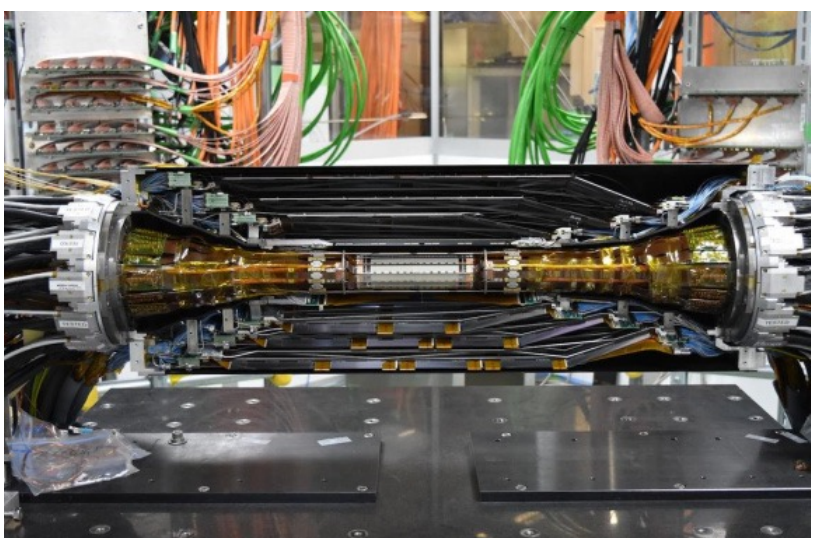
Current state of Belle II

Detector and *accelerator upgrades* during Long Shutdown I (LS1) and preparing to restart SuperKEKB in late January with Collisions restarting in Feb 2024.


Installation of the upgraded PXD2


Replacement of CDC HV bias resistor


Replacement of iTOP MCP-PMTs

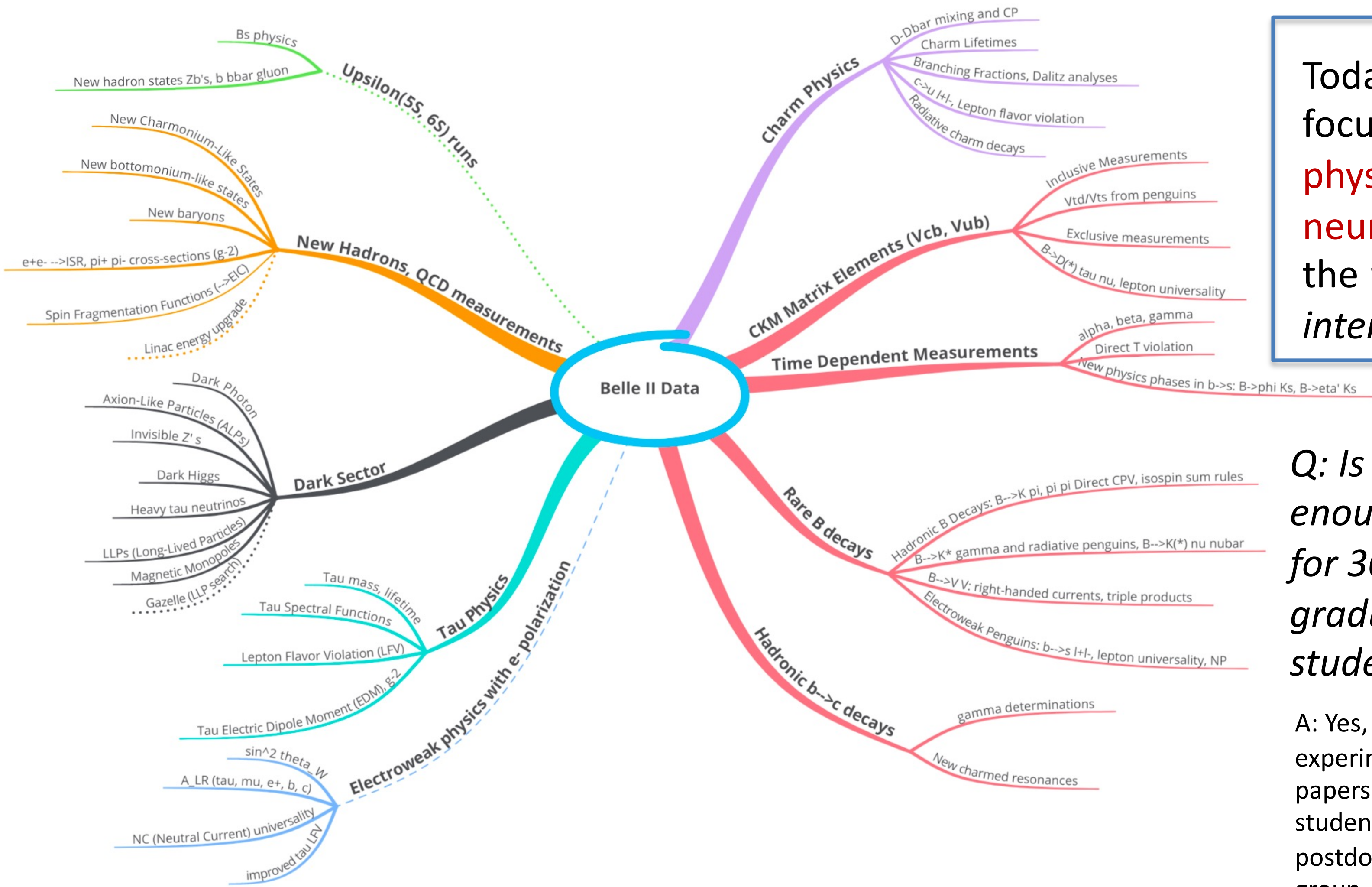


PXD2 installation completed Aug 4, 2023

https://www.interactions.org/press-release/made-germany-worlds-thinnest-pixel-vertex-detector-installed

Belle II Physics "Mind Map" for Snowmass 2022

Wealth of new physics possibilities in different domains of HEP (weak, strong, electroweak interactions). Many opportunities for *initiatives* by young scientists.



Today, we focus on the B physics neurons and the *weak interaction*.

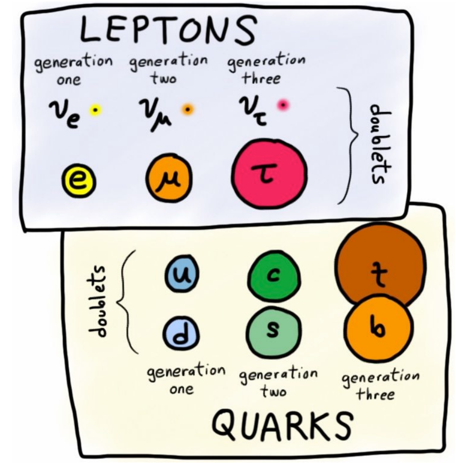
Q: Is there really enough physics for 300 graduate students ?

A: Yes, c.f. B factory experiments, >600 papers. Most by Phd student/advisor, postdoc or small group.

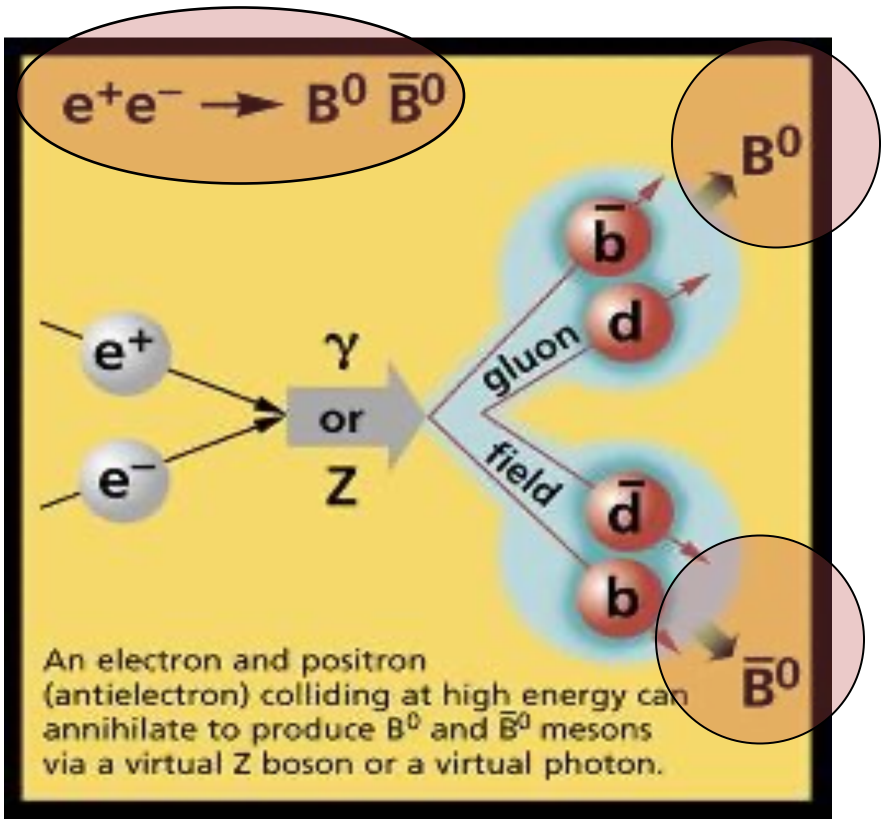
Dashed lines indicate extensions to SuperKEKB/Belle II that can enhance the physics reach of the facility. WP's https://confluence.desy.de/display/BI/Snowmass+2021

B mesons:
"Laboratory rats of the weak interaction"

"Breed large numbers and watch them die"

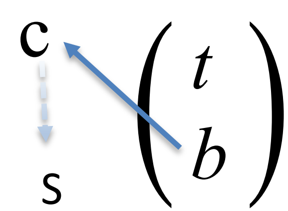


At the ϒ(4S), B Bbar pairs are produced with NO additional particles.



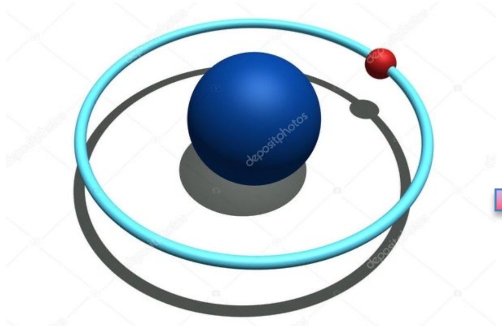
Exotic bound state of matter and antimatter (hydrogen-like)
b quark mass ~ 5 x proton mass

Lifetime ~ 1.5ps

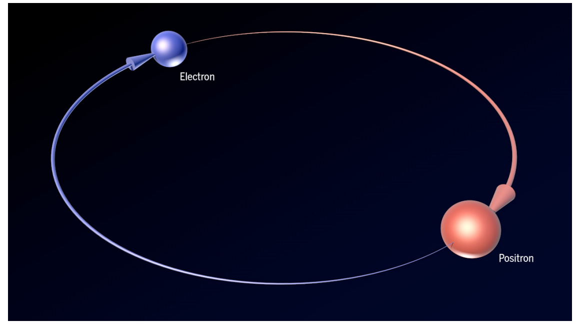


More on this in a moment

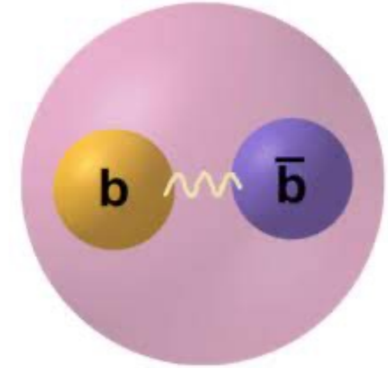
1987: ARGUS@DESY found that the neutral B meson can transform into its *anti-particle*, "B-Bbar mixing"



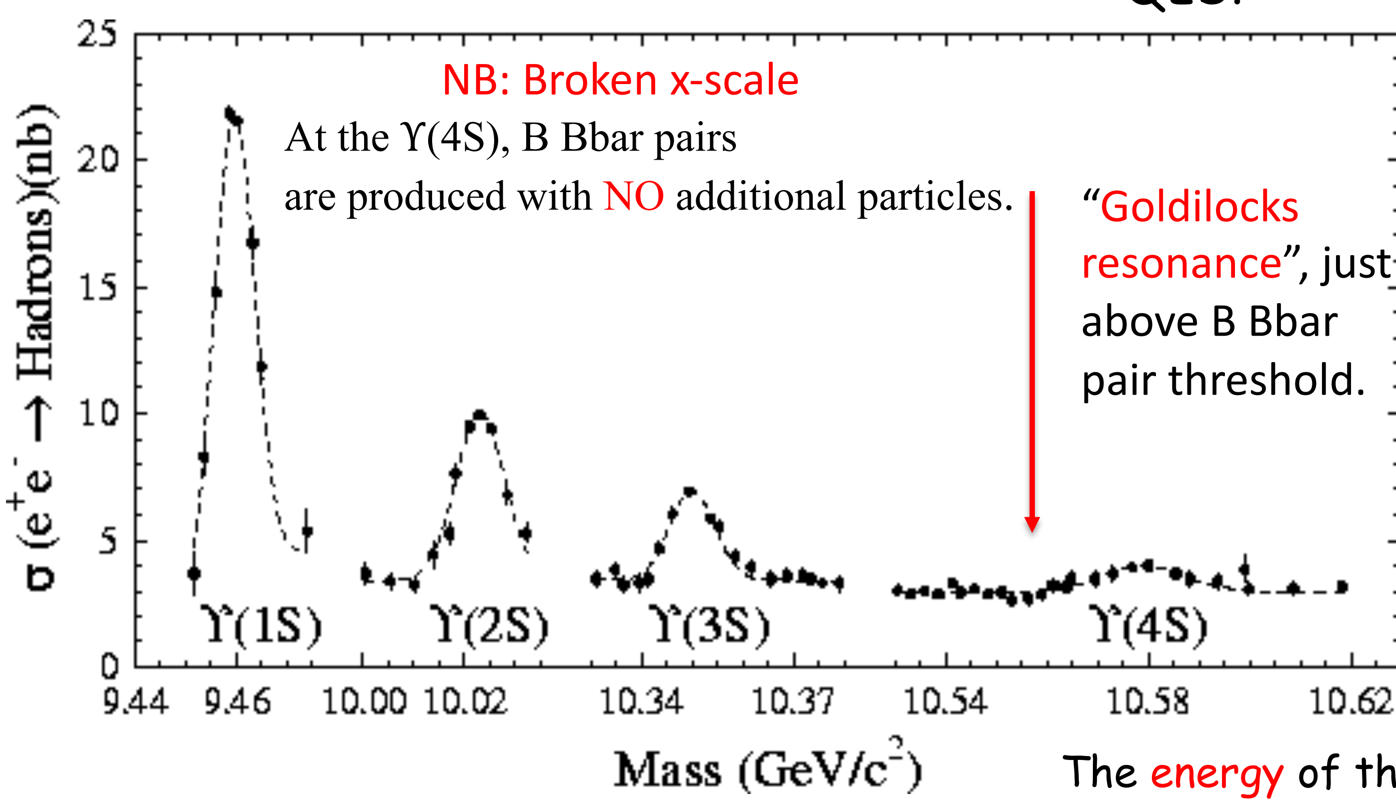
Hydrogen (p and electron bound state)



Positronium (e+e- bound state)



Bottomonium (b bar bound state), QCD instead of QED.



The energy of the e+e- machine is tuned to the ϒ(4S) resonance

Particle-Antiparticle Mixing

Start with a B^0 (wait a while, a few x 10^{-12} sec)

There is a large probability it will turn into its anti-particle, an anti-B^0 i.e.

$$B^0 \rightarrow \bar{B}^0$$

$$\begin{cases} x_d = 0.769 \pm 0.004 & (B_d^0\text{–}\overline{B}_d^0 \text{ system}) \\ x_s = 26.89 \pm 0.07 & (B_s^0\text{–}\overline{B}_s^0 \text{ system}) \end{cases},$$

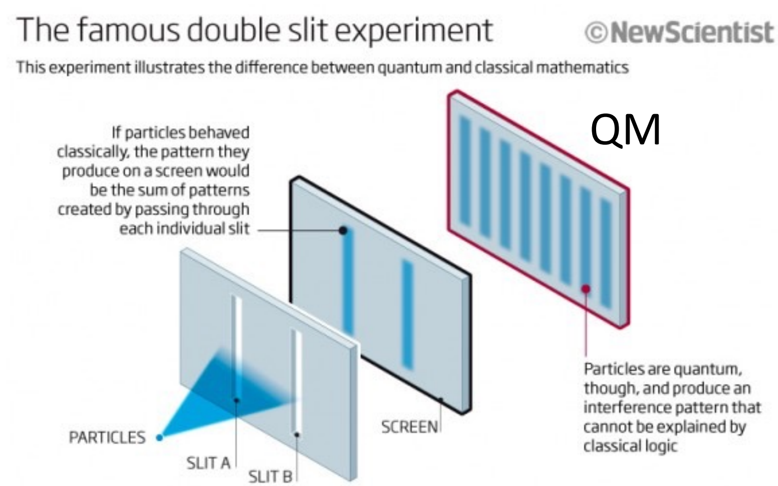
This also happens with K^0 (strange quarks) and D^0 (charm quark) mesons.

x (%)	$0.50^{+0.13}_{-0.14}$
y (%)	0.62 ± 0.07

Let's add in Quantum Mechanical Interference

"We choose to examine a phenomenon which is impossible, absolutely *impossible*, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery."

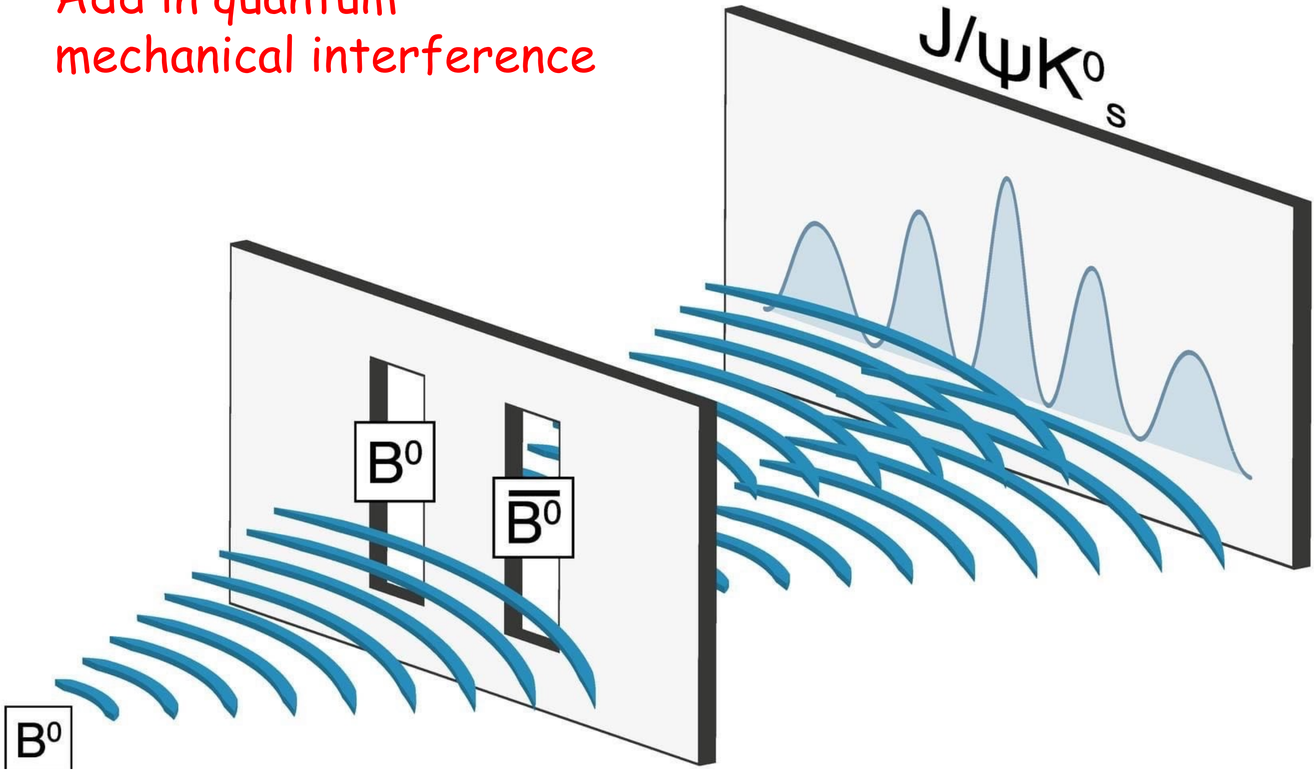
--Richard P. Feynman



Even for single electrons

Figure from CERN LHCb outreach (also see Hazumi 2001)

Add in quantum mechanical interference



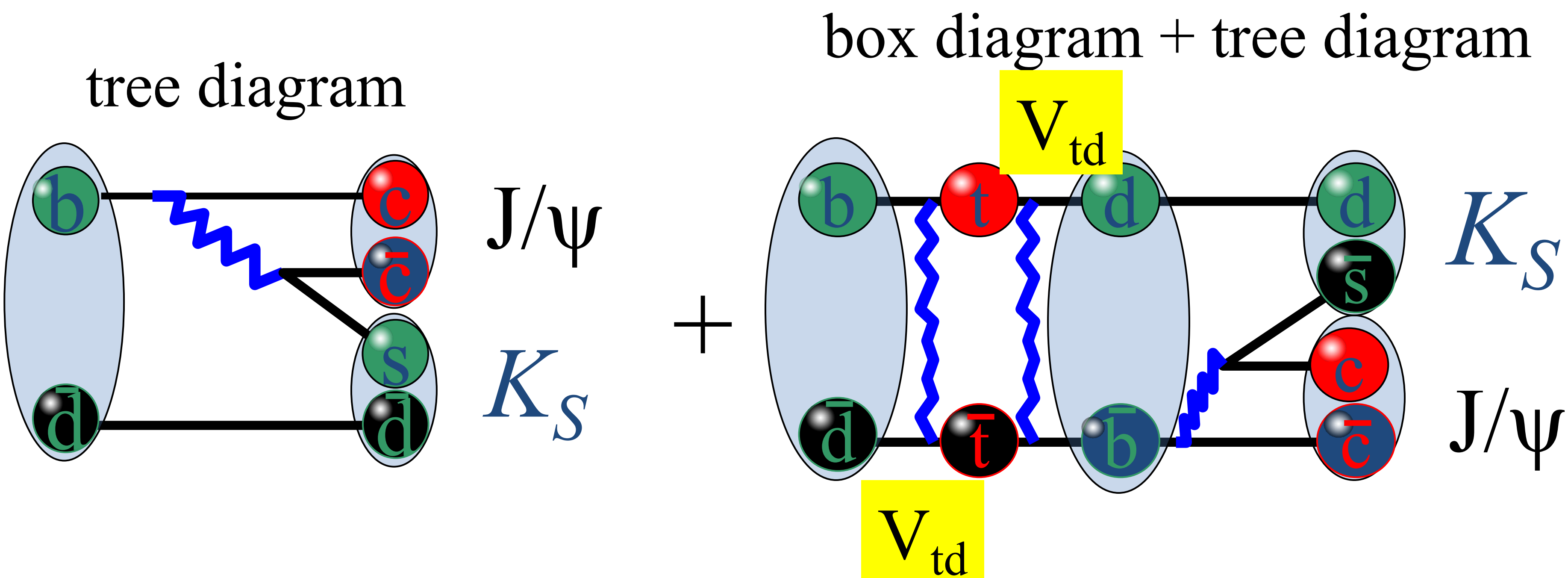
Q: But how can we get a phase difference between the two paths (so that there is an interference pattern on the screen) ?

Ans: $B^0 \rightarrow J/\psi$ Ks *and*
$B^0 \rightarrow \bar{B}^0 \rightarrow J/\psi$ Ks (via particle-anti particle mixing). These two paths have different weak interaction phases.

Another way of looking at this: Time-dependent *CP* violation is

"*A Double-Slit experiment*" with particles and antiparticles

QM interference between two diagrams

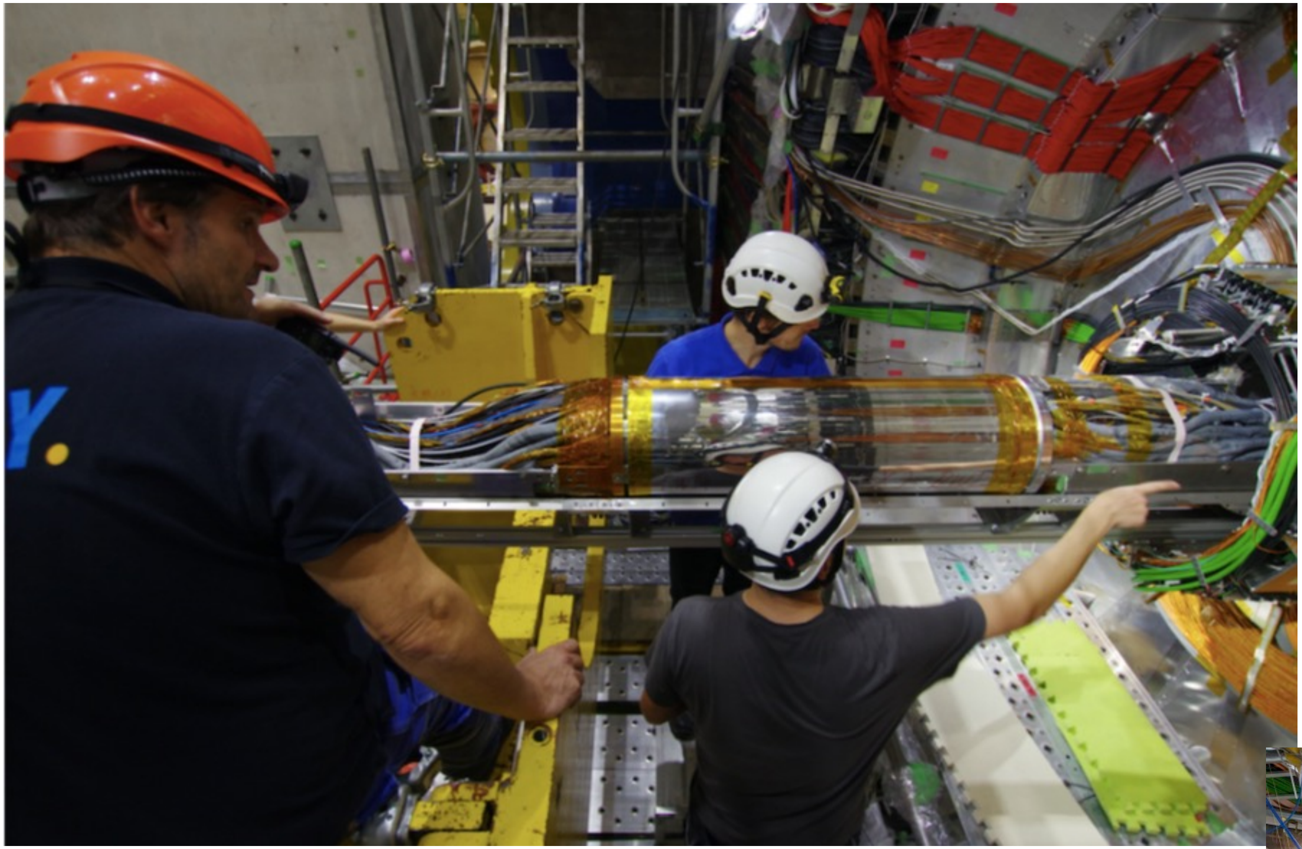


Measures the phase of V_{td} or equivalently the phase of $B^0 \to \bar{B}^0$ mixing.

Time Dependent Measurements at Belle II

"Pain et beurre" (i.e .bread and butter) for the B factories.

"misoshiro to gohan" ?

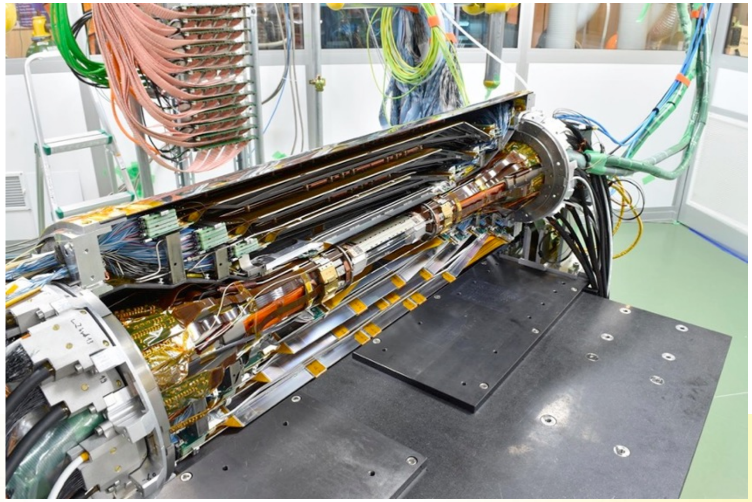


Belle II VXD installed on Nov 21, 2018. (PXD L1 and two ladders of L2. and the SVD (4 layers))

LS1: VXD upgrade

Recent time-dependent measurements from Belle II:
https://arxiv.org/abs/2302.12898 (CPV in b-->c cbar s)
https://arxiv.org/abs/2302.12791 (B-Bbar mixing)
and time-dependent papers on CPV in B→ϕ Ks, Ks π0, Ks Ks Ks
In 2023 and 2024 use PXD1 and the pre-LS1 dataset.

B→J/ψ K_S and the road to CPV



We use a "Golden" CP Eigenstate

$$B^0 \to J/\psi K_S$$

$$\Delta t \approx \frac{\Delta z}{\beta\gamma}$$

$$B^0 \to f \; ; B^0 \to \overline{B^0} \to f$$

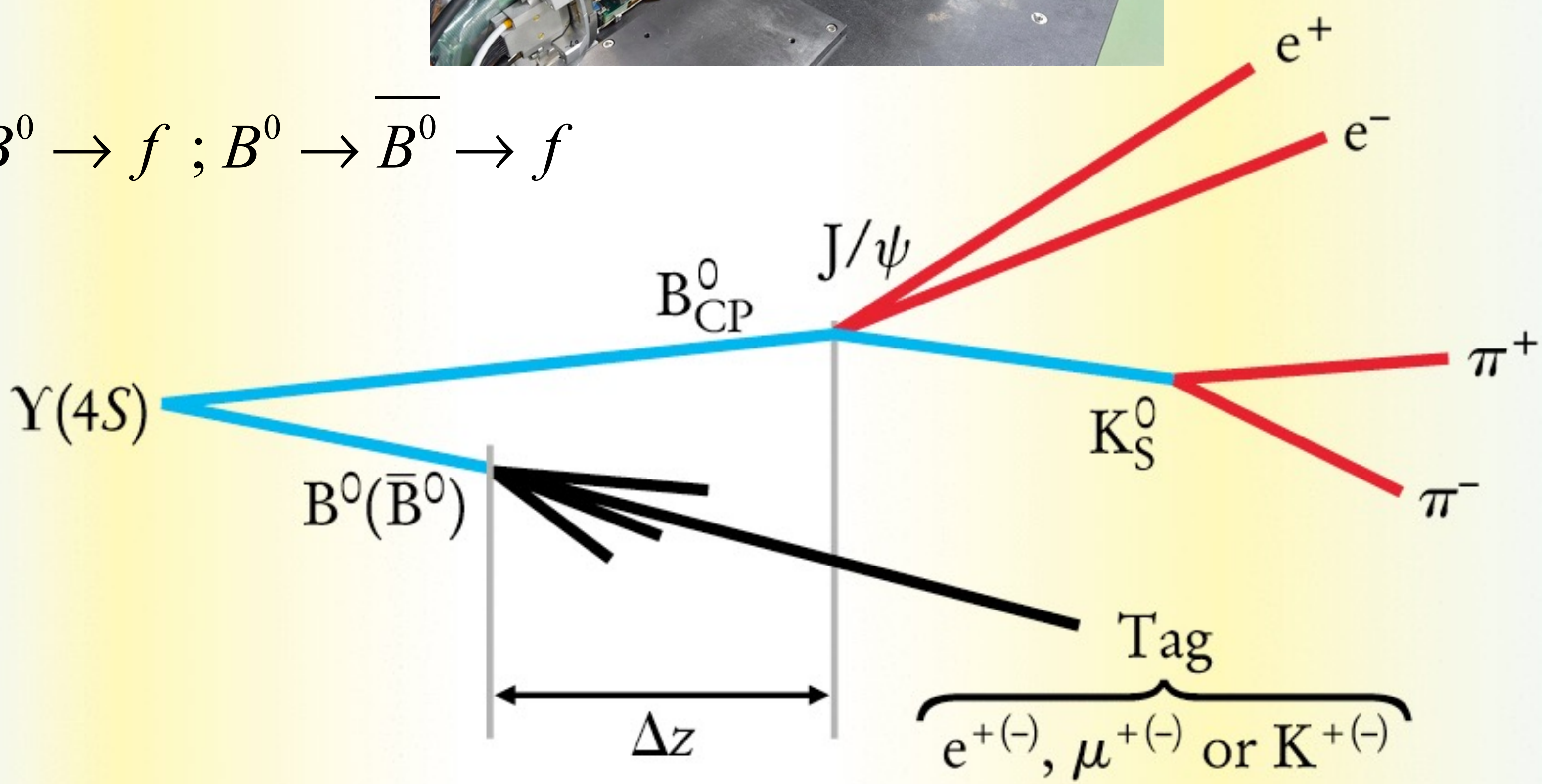
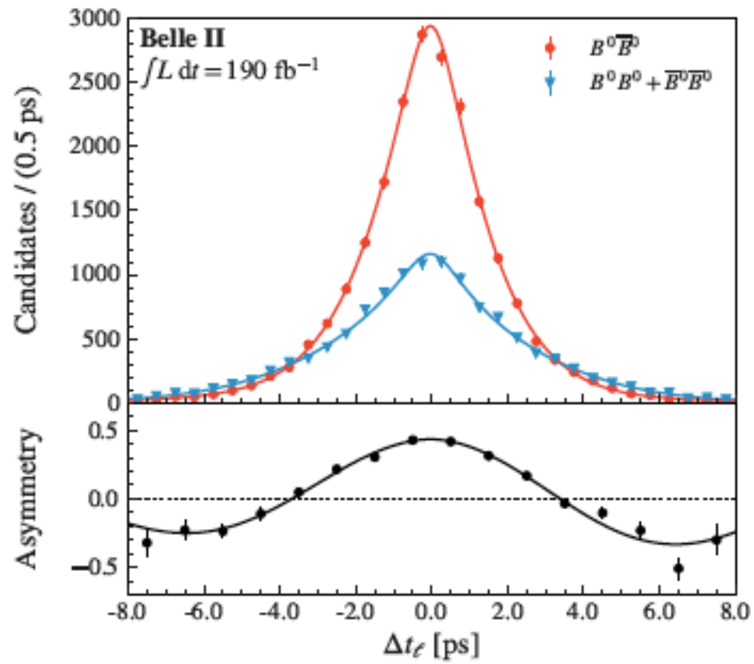


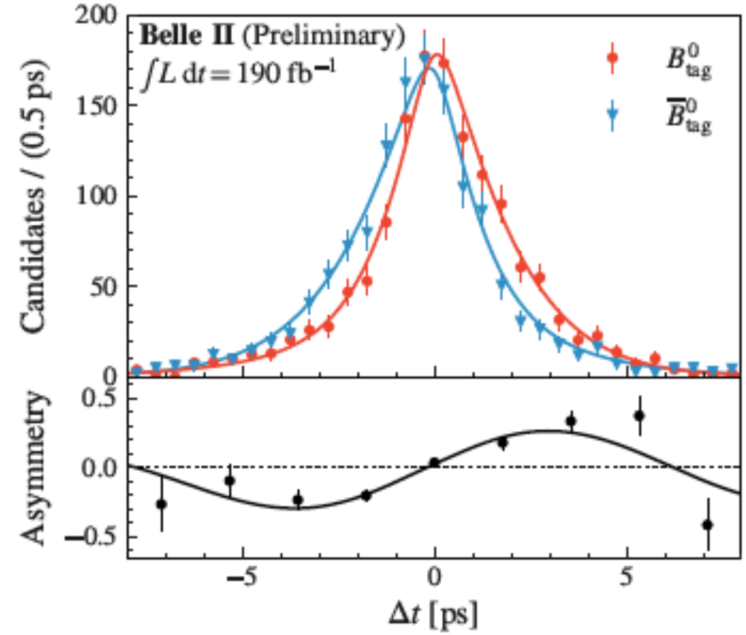
Figure credit: Physics Today

Verification of B-Bbar mixing (particle-anti particle mixing) in Belle II data (*not CPV*)

Verification of mixing induced CP Violation in Belle II data

$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\mathrm{ps}^{-1}$$





https://arxiv.org/abs/2302.12791

https://arxiv.org/abs/2302.12898

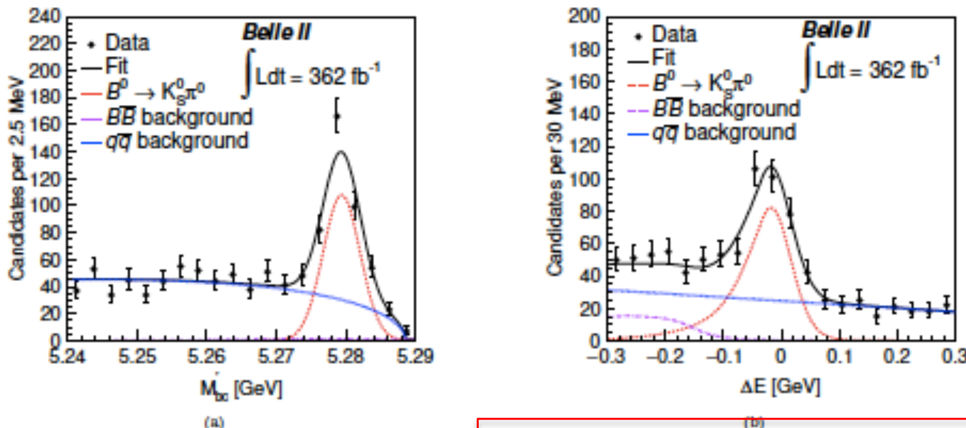
Figure 1 – Projections of the Δt fit on the $B^0 \to D^{(*)-}\pi^+$ (left) and $B^0 \to J/\psi K^0_S$ (right) samples.

$$N_{SF/OF} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}[1 \pm (1-2w)\cos(\Delta m_d \Delta t)] \otimes R(\Delta t)$$

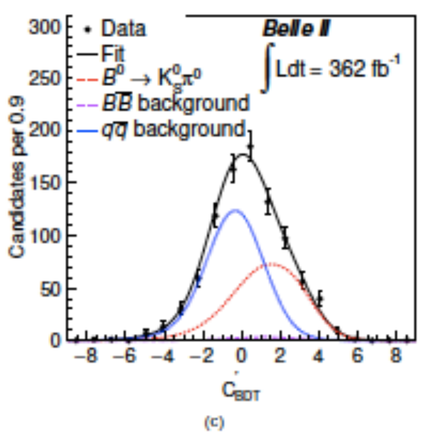
$$N_{+/-} \sim \frac{\exp(-|\Delta t|/\tau)}{4\tau}\{1 \pm (1-2w)\sin(2\phi_1)\sin(\Delta m_d \Delta t)\} \otimes R(\Delta t)$$

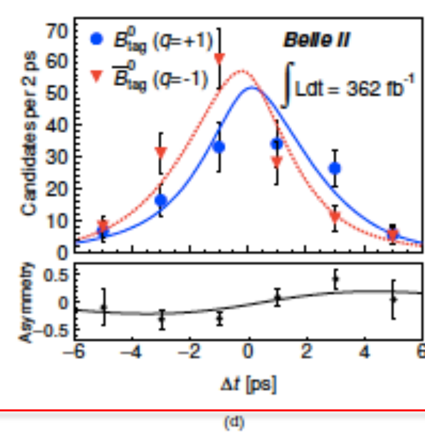
$$\sin(2\phi_1)[\sin(2\beta] = 0.720 \pm 0.062(stat) \pm 0.016(sys)$$

Belle II has results for B→Ks π^0, ϕ Ks, η' Ks, Ks Ks Ks time-dependent CPV in b→s q qbar transitions. These are statistics limited.



Here is one example from a recent PRL (Phys. Rev. Lett 131, 111803 (2023))

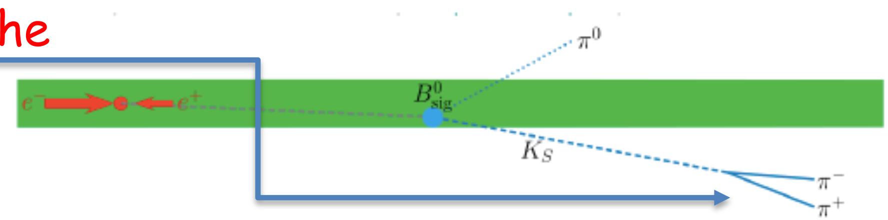




$$S = 0.75^{+0.20}_{-0.23} \pm 0.04$$

$$C = -0.04^{+0.14}_{-0.15} \pm 0.05$$

Idea: Ks vertexing in the silicon with the beam spot constraint.



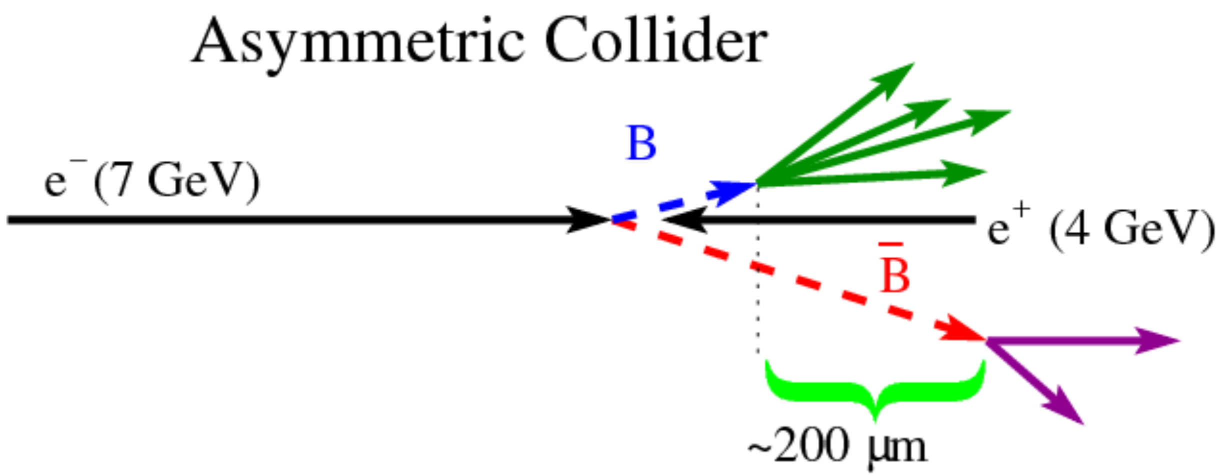
The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a coherent, *entangled* **quantum mechanical state.**

$$|\Psi>=|B^0(t_1,f_1)\overline{B^0}(t_2,f_2)> - |B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

(Why is there a minus sign ?)

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B. (N.B. One B must decay before the other can mix) [*why ?*]

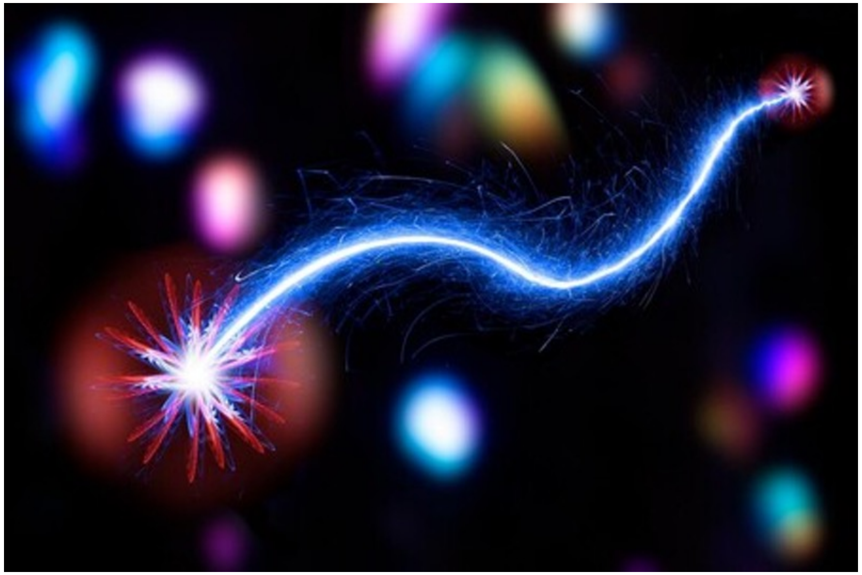


Not to scale

The beam energies are asymmetric (7 on 4 GeV)

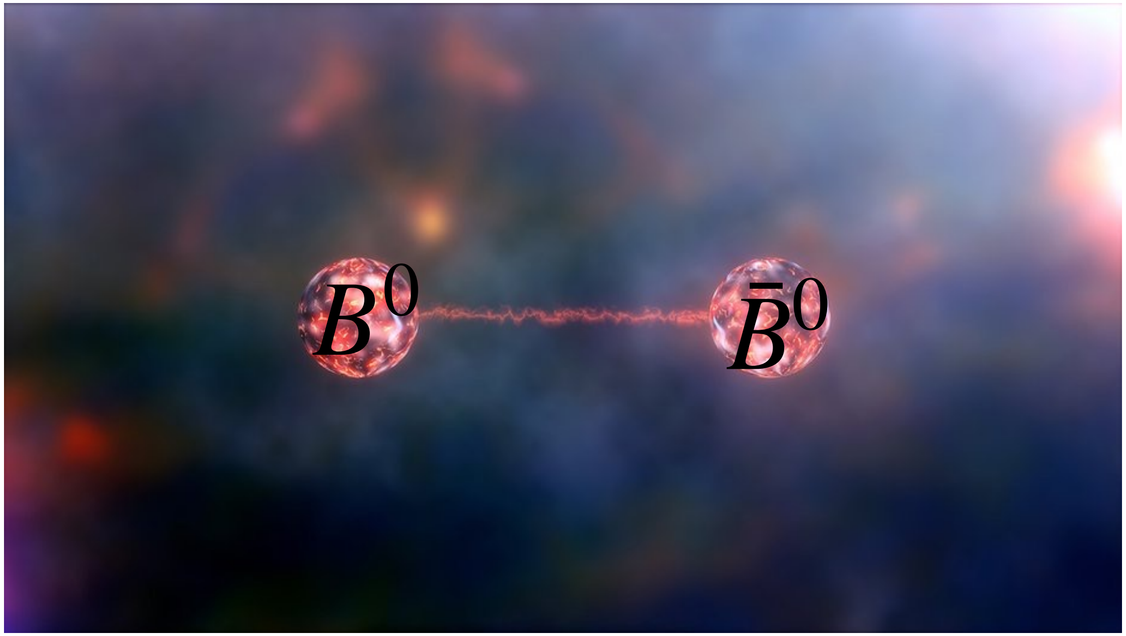
The decay distance is increased by around a factor ~7

Reminder: Quantum Mechanical Entanglement



Each B^0-anti B^0 pair is an Einstein-Podolsky-Rosen (EPR) experiment.
Time dependence of mixing is determined by this.

Figure credit: V. de Schwanberg/sciencesource.com



Original from Caltech outreach

The B^0-anti B^0 meson pairs at the Upsilon(4S) are produced in a <u>coherent</u>, *entangled* **quantum mechanical state.**

$$|\Psi> = |B^0(t_1,f_1)\overline{B^0}(t_2,f_2)> - |B^0(t_2,f_2)\overline{B^0}(t_1,f_1)>$$

Ans: C=-1

Need to measure decay times to observe CP violation (particle-antiparticle asymmetry).

One B decays →collapses the flavor wavefunction of the other anti-B.
(N.B. One B must decay before the other can mix) [Ans: otherwise the overall wavefunction is zero]

The Nobel Prize in Physics 2022

Ill. Niklas Elmehed © Nobel Prize Outreach
Alain Aspect
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
John F. Clauser
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
Anton Zeilinger
Prize share: 1/3

Nobel Prize for "QM Entanglement"

Each B^0-anti B^0 pair is an Einstein-Podolsky-Rosen (EPR) experiment.

Belle checked for the breakdown of QM in https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.131802
https://arxiv.org/abs/quant-ph/0702267

Q: Can Belle II do more on QM entanglement ?

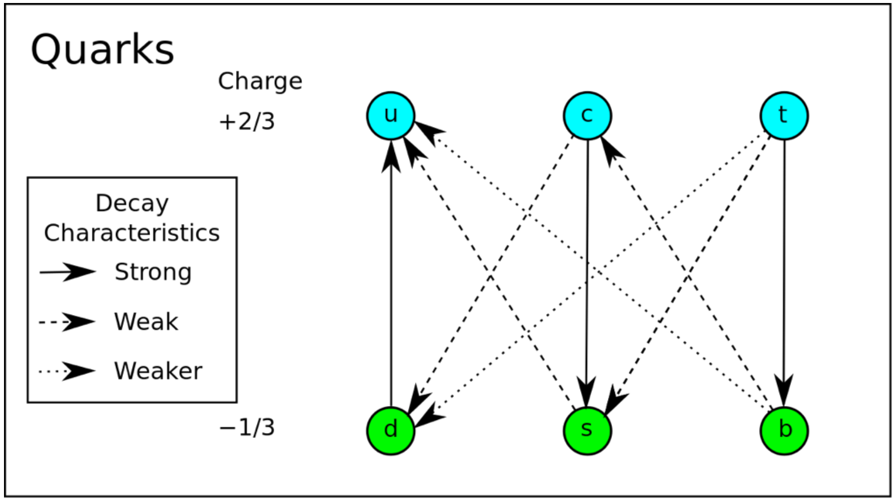
Let's review a few weak interaction fundamentals that are needed to understand Belle II Physics.

Q: What is a rare decay of a B meson ?

Ans 1: A decay that is suppressed.

But compared to what ?

Ans: **Suppressed compared to a decay involving a b→c transition**, which is dominant (since b is a "down-type quark").



Q: So which transitions give rise to rare decays ?

Ans 1: *Decays that involve a jump in generations (extra CKM suppression)*

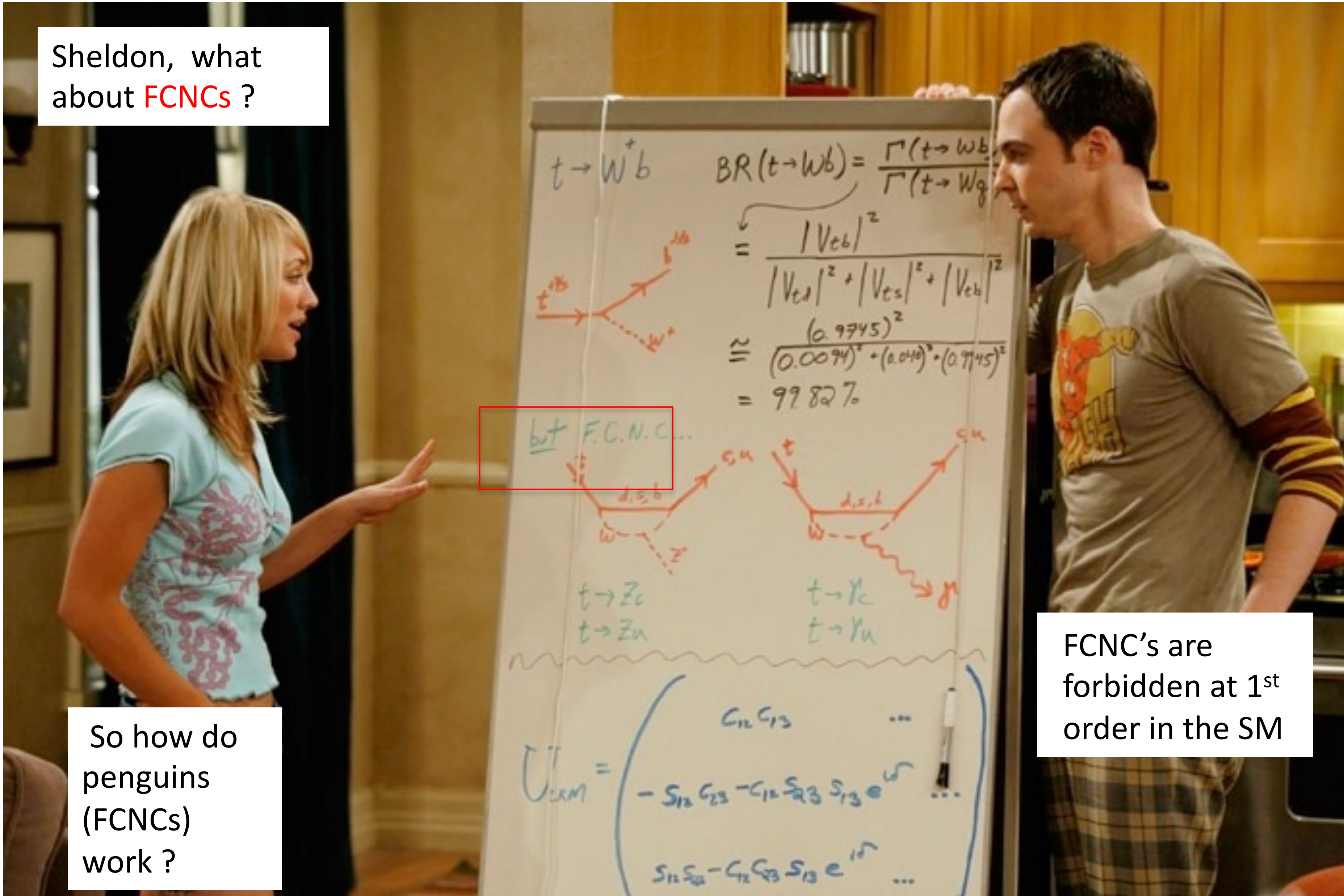
Ans 2: b→u decays

Q: But what about b→s or b→d transitions, why aren't they shown here ?

Spoiler Alert: They do not occur at 1st order in the weak interaction.

Please remember strong decays do not change flavor.

Old US TV Show, Big Bang Theory Episode (FCNCs)

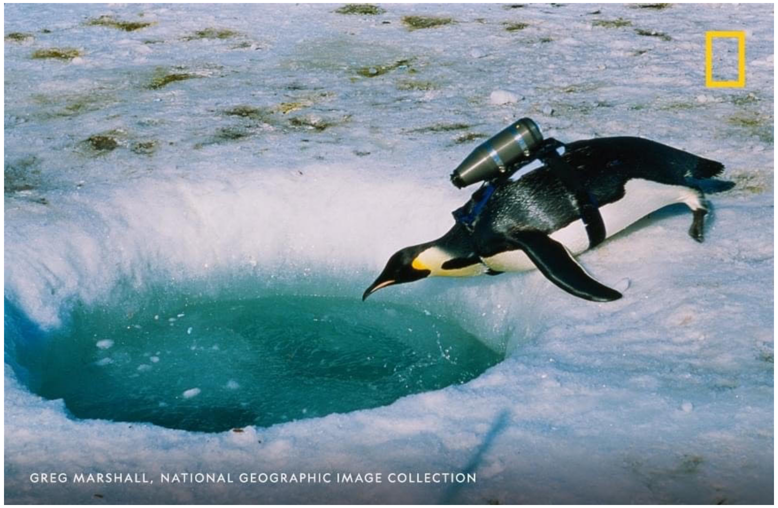


Whiteboards by Prof. David Saltzberg (UCLA)

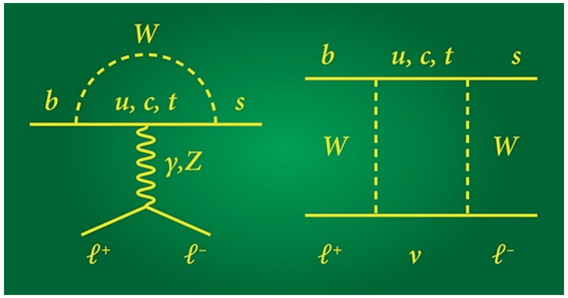
At Snowmass 2022 (the decadal survey of HEP) we considered how Belle II might discover BSM physics

Research penguin

Photo Credit: National Geographic

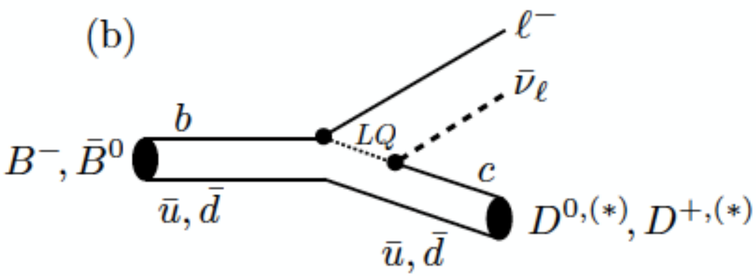


Exploring the unknown with b→s "electroweak penguins": (weak neutral current or FCNC)



Sequoia National Forest

Discovering NP with b→c l ν "trees": (weak charged current)



Radiative Penguins at Belle II

1975: Vainshtein, Zakharov and Shifman

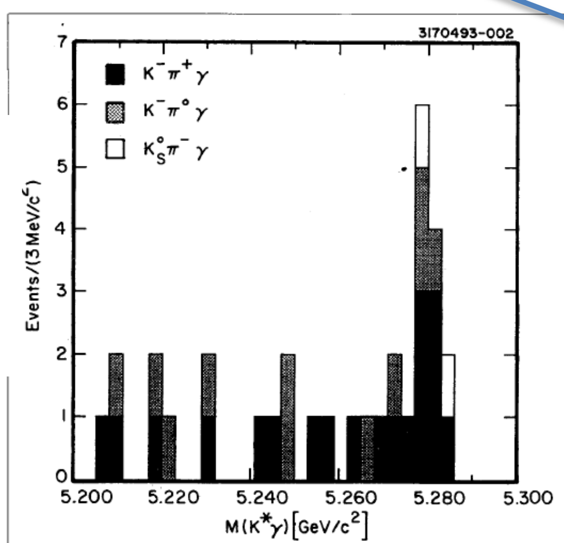
Examine the following $b \to s\ \gamma$ decay modes in the Belle II Phase 3 dataset.

$$B^0 \to K^{*0}\gamma \to K^+\pi^-\gamma$$
$$B^+ \to K^{*+}\gamma \to K^+\pi^0\gamma$$
$$B^+ \to K^{*+}\gamma \to K_S^0\pi^+\gamma$$

John Ellis, the CERN theorist who coined the name "Penguin" (a type of FCNC).

1993 CERN Courier:

CORNELL
CLEO discovers
B meson penguins



N.B. Using 1.5 x 10^6 B meson pairs (1.5 fb^{-1})/ less than Belle II/day

Belle II's CsI(Tl) calorimeter (~Belle with improved waveform sampling and timing). 8736 crystals covering 90% of the solid angle.

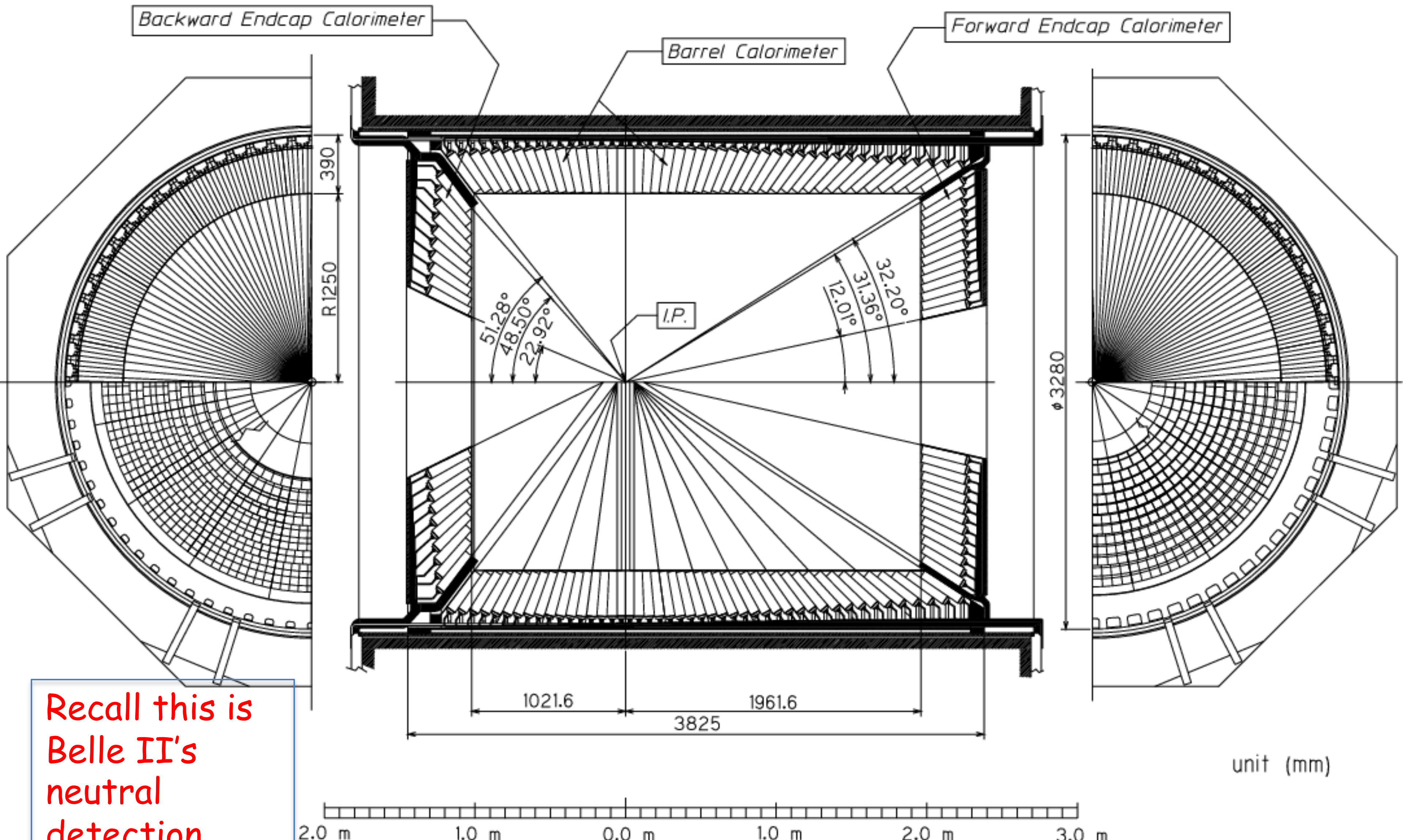


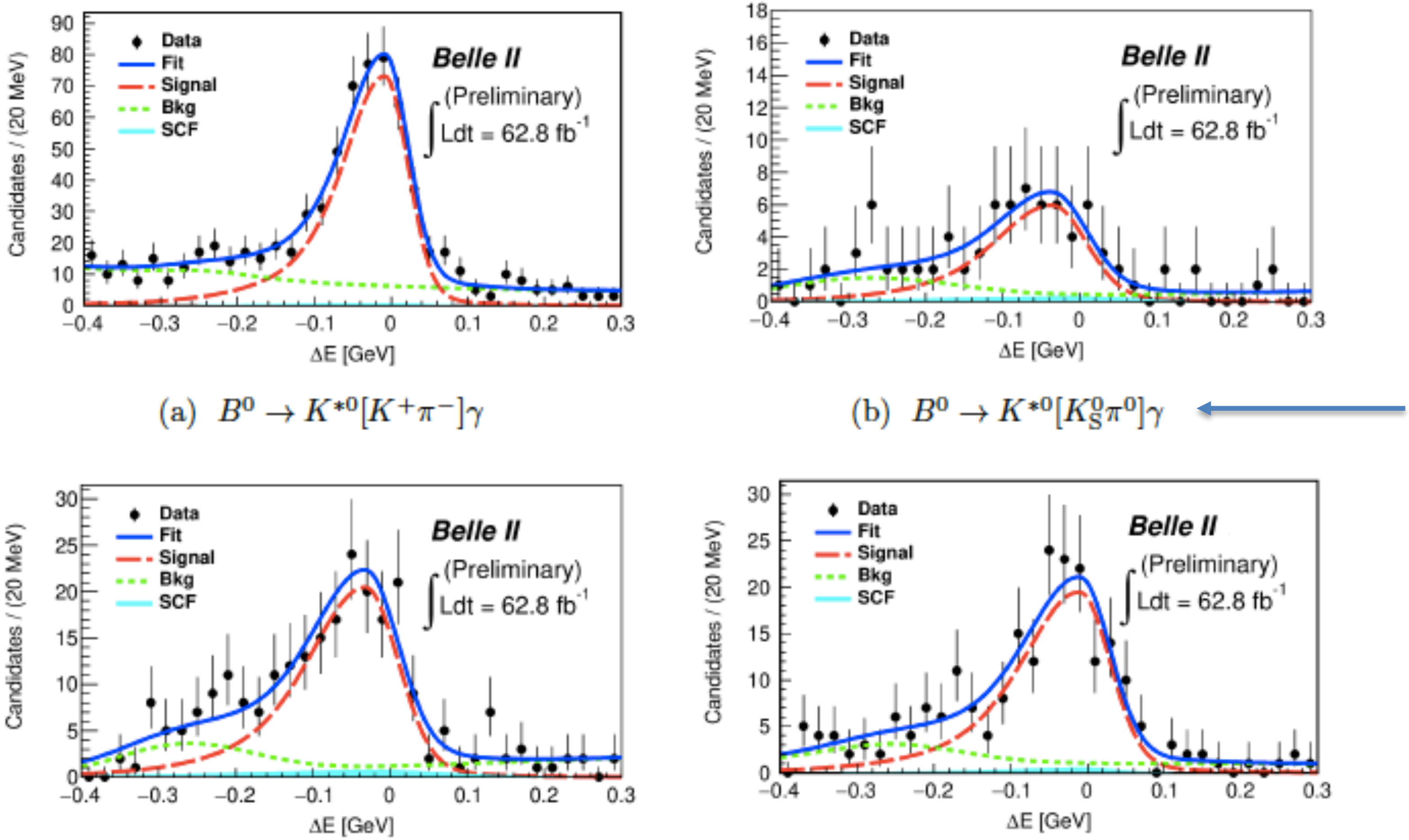
Fig. 69. Overall configuration of ECL.

Recall this is Belle II's neutral detection superpower

Belle II, 2021

$$\Delta E = E_{recon} - E_{beam}$$

BELLE2-CONF-2021-028, Radiative Penguins reconstructed using the ECL



(a) $B^0 \to K^{*0}[K^+\pi^-]\gamma$

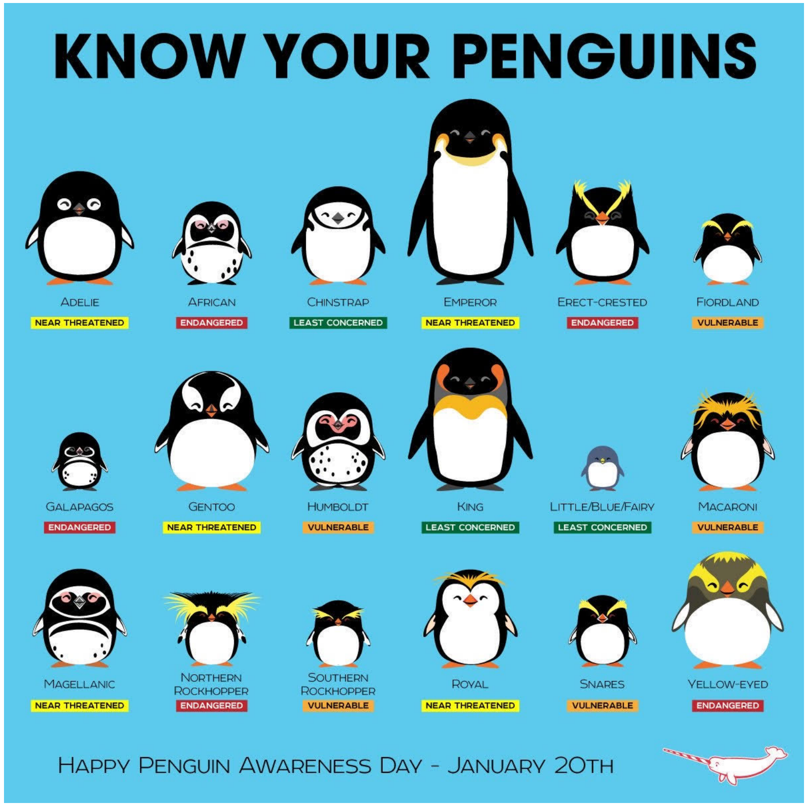
(b) $B^0 \to K^{*0}[K^0_S\pi^0]\gamma$

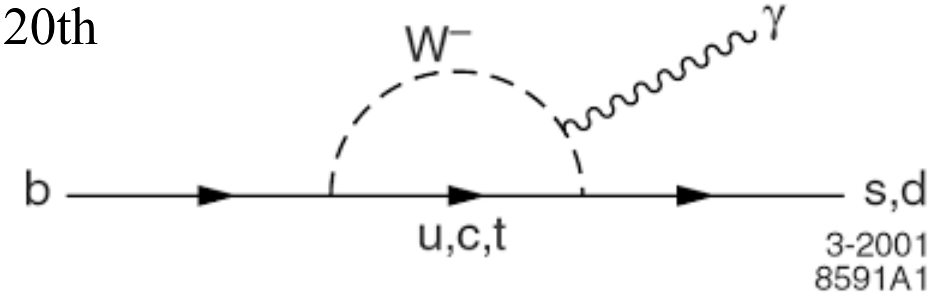
(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$

(d) $B^+ \to K^{*+}[K^0_S\pi^+]\gamma$

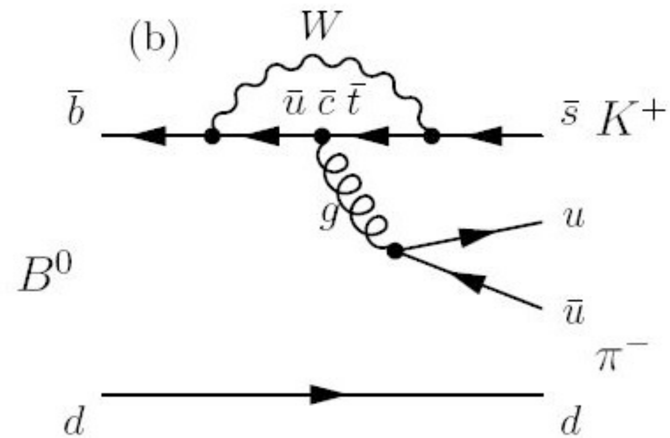
Figure 2. ΔE distributions for each $B \to K^*\gamma$ mode with the fit result superimposed. The black dots with error bars denote the data, the blue curve denotes the total fit, the dashed red curve is the signal component, the dotted green curve is the background component, and the filled cyan region is the misreconstructed signal component.

Recap for "Penguin Awareness Day", Jan 20th

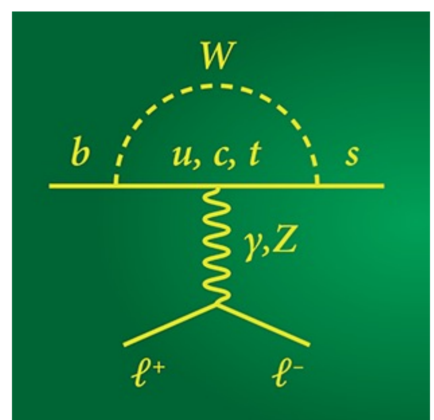




"Radiative Penguin"
(b→s γ)



"Gluonic Penguin"
(b→s gluon)



Q: But there is one more in our penguin taxonomy. Do you remember what it is?

Ans. Electroweak Penguins.
e.g. b→s [Z*, γ^*]→s l+ l-

nature Vol 452|20 March 2008|doi:10.1038/nature06827

An old anomaly:

LETTERS

In 2008, "the K π puzzle" appeared in Nature.
Charged and neutral A(CP's) for B→Kπ penguins differ. Is this a sign of new physics ? *How do we tell ?*

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

Also confirmed by BaBar and then LHCb

A_{CP}			
Mode	BaBar	Belle	LHCb
$K^+\pi^-$	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	$-0.069 \pm 0.014 \pm 0.007$	$-0.080 \pm 0.007 \pm 0.003$
$K^+\pi^0$	$0.030 \pm 0.039 \pm 0.010$	$0.043 \pm 0.024 \pm 0.002$	0.025+-0.015+0.006
$K^0\pi^+$	$-0.029 \pm 0.039 \pm 0.010$	$-0.011 \pm 0.021 \pm 0.006$	$-0.022 \pm 0.025 \pm 0.010$
$K^0\pi^0$	$-0.13 \pm 0.13 \pm 0.03$	$0.14 \pm 0.13 \pm 0.06$	

In summary, we have measured the CP asymmetries for $B\to K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^0$ and $\pi^{\pm}\pi^0$ using 535 million $B\bar{B}$ pairs. Direct CP violation in $B^{\pm}\to K^{\pm}\pi^{\mp}$ is observed, accompanied by a large deviation between $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ and $\mathcal{A}_{K^{\pm}\pi^0}$. Although this deviation could be due to our limited understanding of the strong interaction, the difference in direct CP asymmetries for charged versus neutral *B* decays may be an indication of new sources of CP violation beyond the standard model of particle physics.

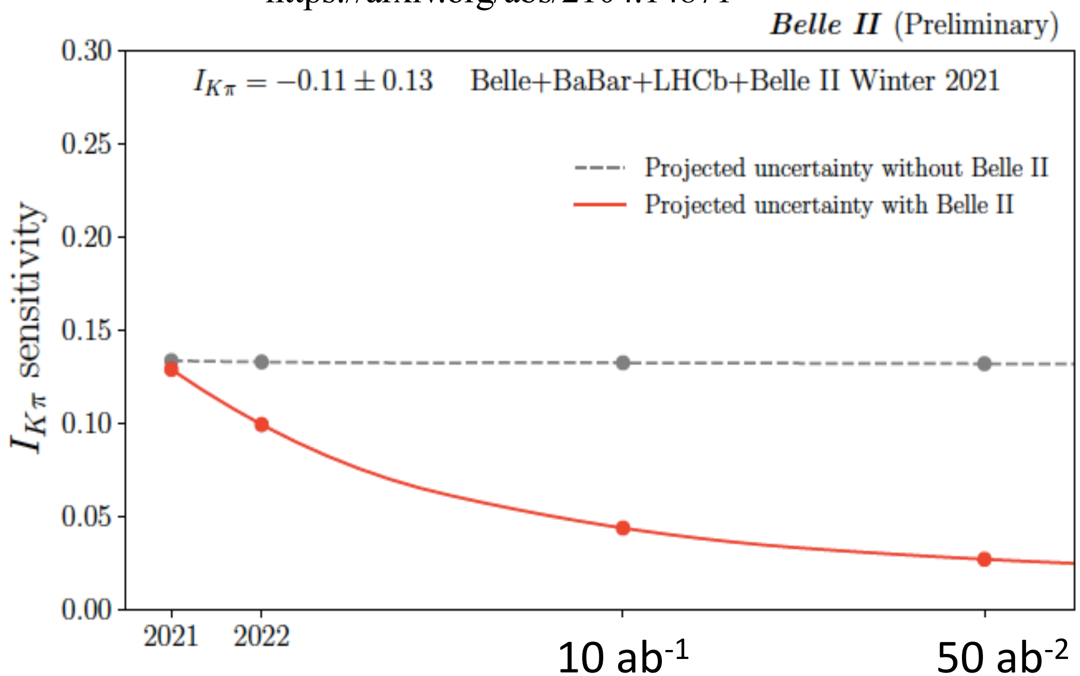
How will we make progress

The isospin sum rule in the next decade.

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

Michael Gronau

https://arxiv.org/abs/2104.14871



The isospin sum rule detects enhanced NP electroweak penguins in $B \to K\pi^-$

Requires neutrals *and* flavor tagging.

Without Belle II measurements of $A_{CP}(B^0 \to K^0 \pi^0)$, we are stuck.

FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements are considered, and the grey curve is the case if only $A_{K^+\pi^-}, A_{K^+\pi^0}, A_{K^0\pi^+}$ are updated by LHCb. The projection corresponds to the luminosity plans from LHCb and Belle II.

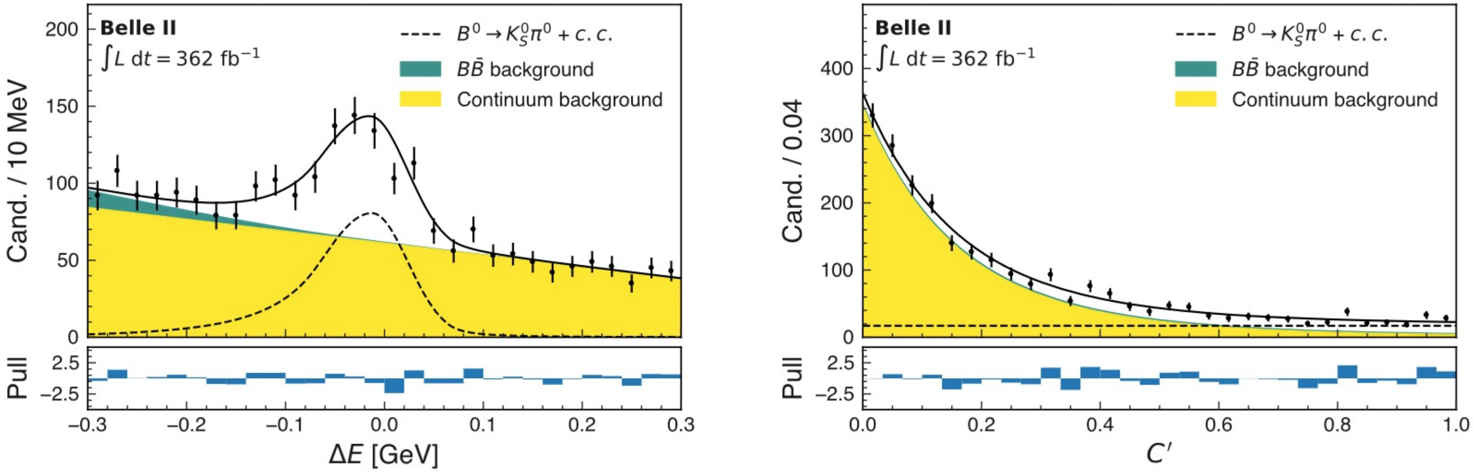
<u>Belle II has *just published* a new result on the B-->h h isospin sum rule.</u>

More on A_{CP} ($B \rightarrow K_S \pi^0$) and the isospin sum rule at Belle II

PHYSICAL REVIEW D **109**, 012001 (2024)

Also https://arxiv.org/abs/2310.06381

Measurement of branching fractions and direct *CP* asymmetries for $B \to K\pi$ and $B \to \pi\pi$ decays at Belle II



Signal yield = 502 ± 32

A_{CP} ($B \rightarrow K^0\ \pi^0$) = -0.06 $\pm 0.15(stat) \pm 0.05\ (syst)$

Time-independent method
(Requires flavor tagging i.e. discrimination of B^0 and anti-B^0).

Combine this with time-dependent result including overlaps and correlations

A_{CP} ($B \rightarrow K^0\ \pi^0$) = 0.04 $\pm 0.15(stat) \pm 0.05\ (syst)$

- Putting all together, we obtain an overall Belle II isospin test:

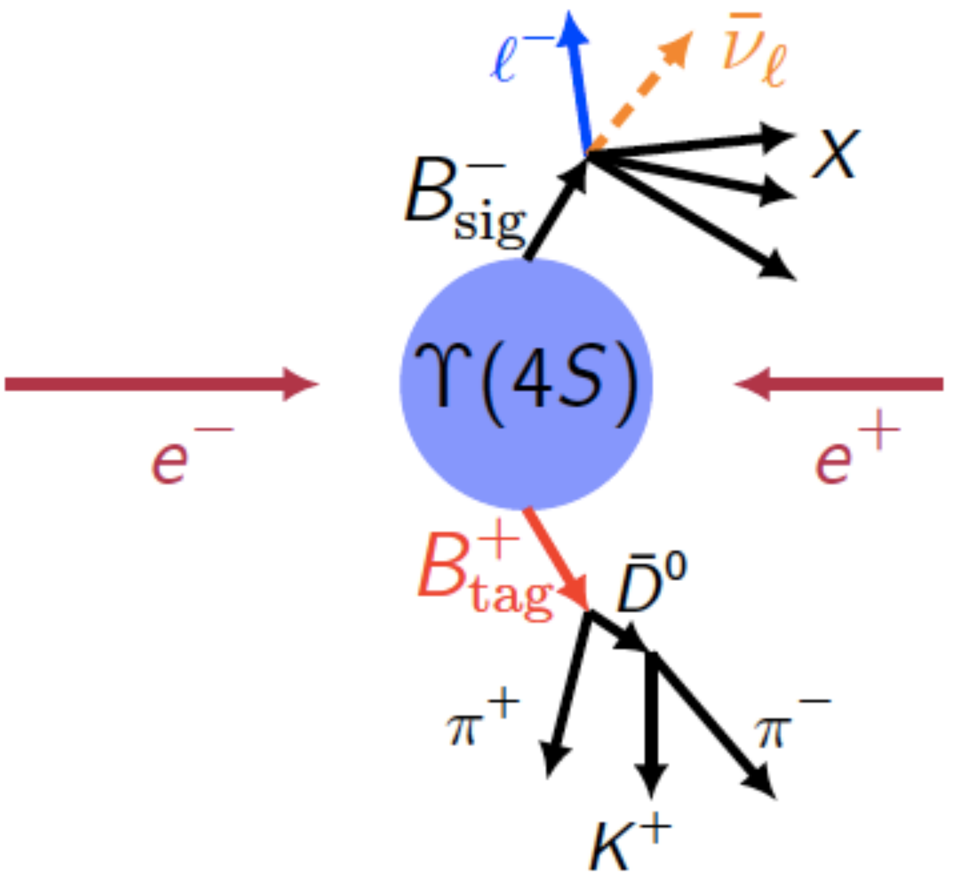
$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.05(syst)$$

Which Belle II capabilities might be relevant for BSM physics ?

Full and equally strong capabilities for electrons and muons

Photons, K_S's with excellent resolution and efficiency

Neutrinos via "missing energy" and missing momentum. Hermeticity.



Another Belle II "Superpower"

https://arxiv.org/abs/2008.06096

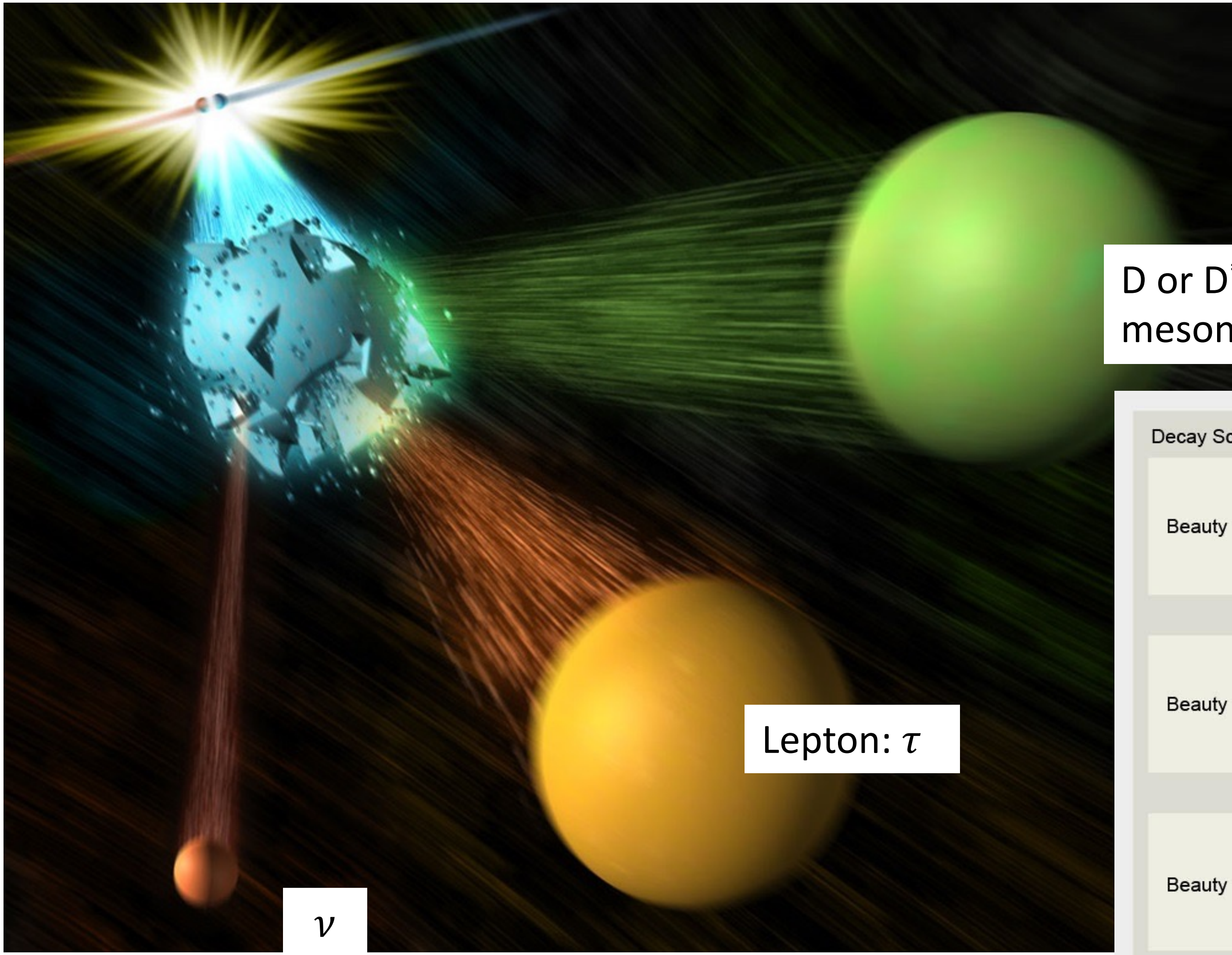
This is now called FEI "Full Event Interpretation" and uses large numbers of tag modes via a BDT (Boosted Decision Tree).

Clean but effiency $\varepsilon \sim 0.5\%$

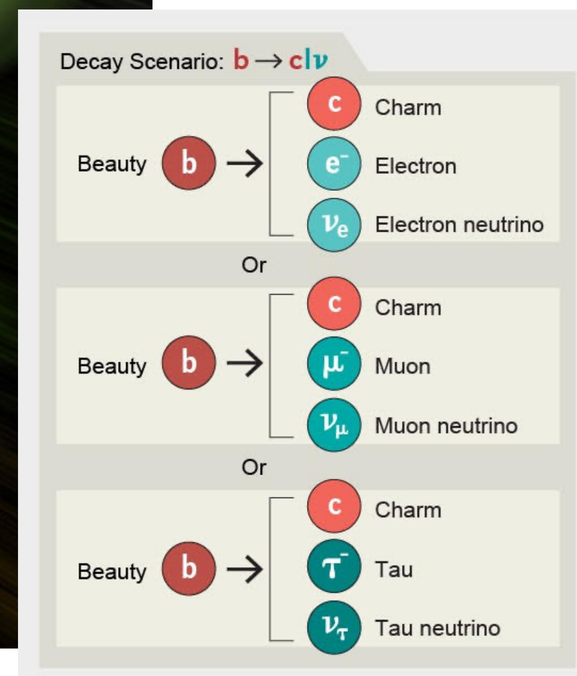
T. Keck et al., Comput. Softw. Big Sci. 3, 6 (2019), arXiv:1807.08680 [hep-ex].

SLAC
Outreach

Possible breakdown of lepton universality in $B \rightarrow D^{(*)} \tau \upsilon$



Lepton Universality

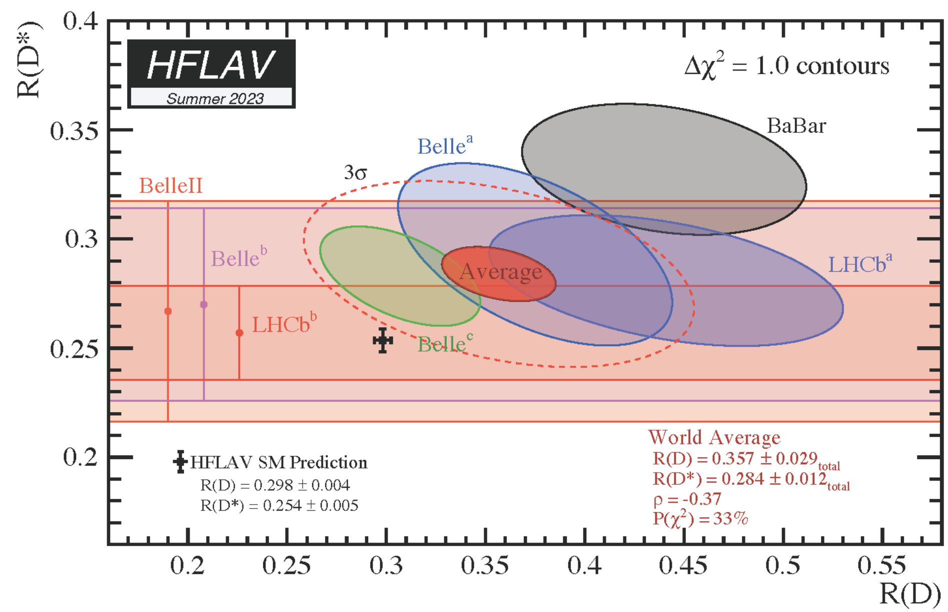


Note this picture has a production process (EM) and a weak decay

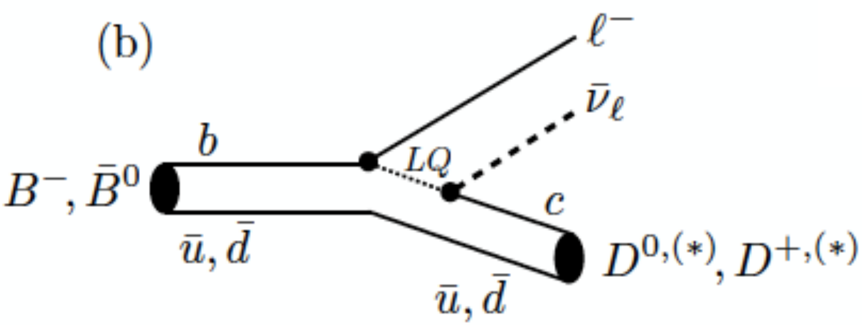
B→D$^{(*)}$ τ υ, possible breakdown of lepton universality

$$R_D^{(*)} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

This might be BSM in the weak b→c charged current



Normally mediated by virtual W charged current.
Some BSM physics possibilities (leptoquarks (LQ), charged Higgs type 3 etc..):



Belle, Belle II, BaBar, LHCb combined: Some evidence of lepton universality breakdown in semileptonic B decays with τ leptons.

With the first Belle II result , the combined deviation is 3.3σ from the SM. (see https://arxiv.org/abs/2401.02840, submitted to PRD.)

Future: Look at q^2, angular distributions to detect BSM physics.

Lepton Universality Tests in b→s l+ l- transitions

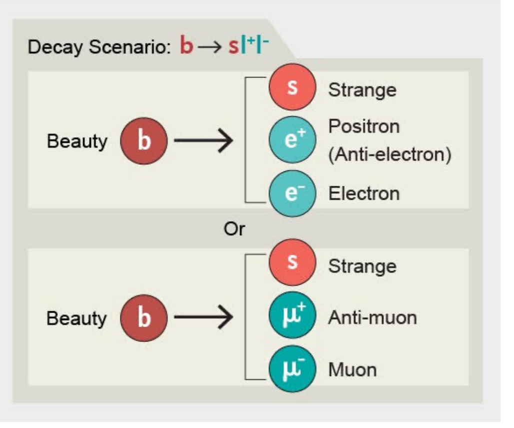
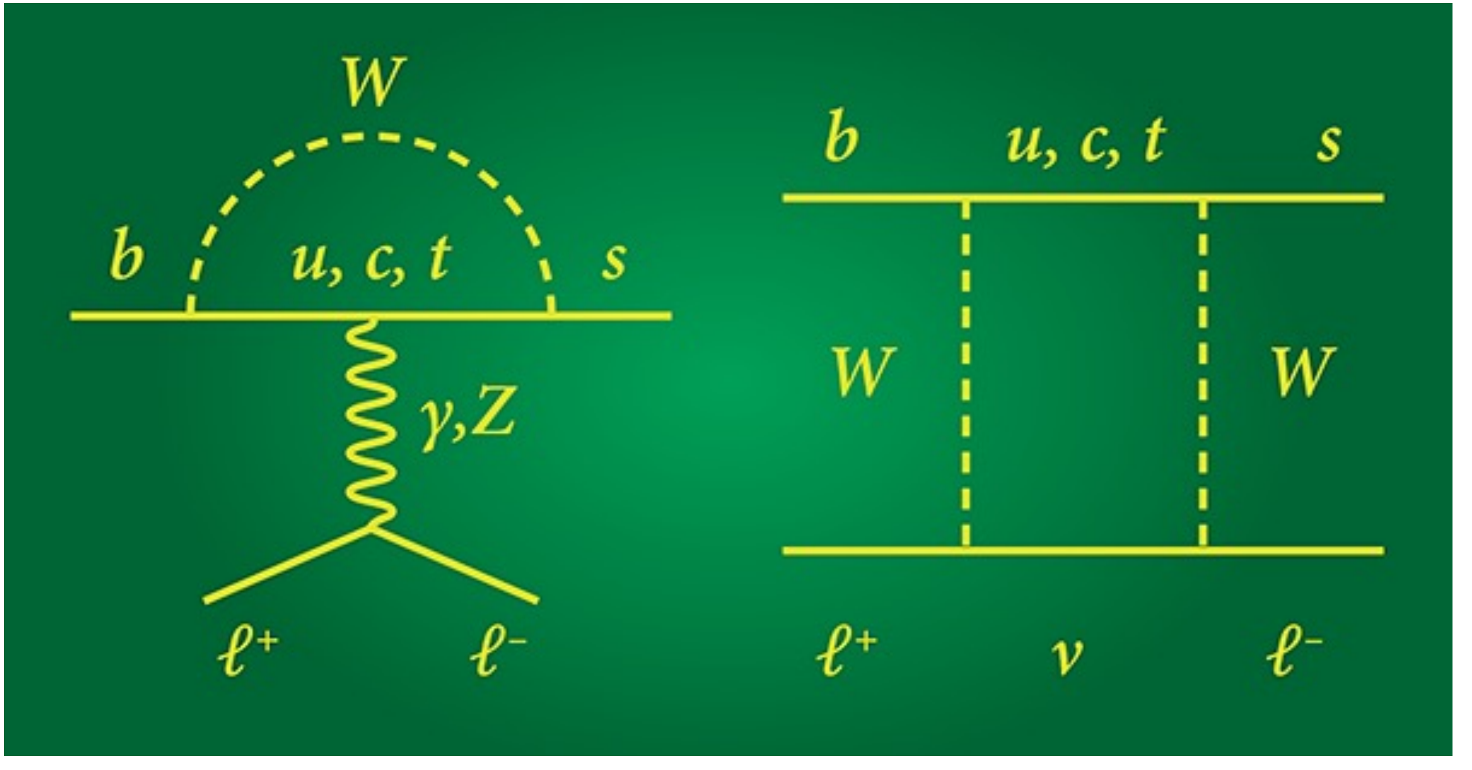


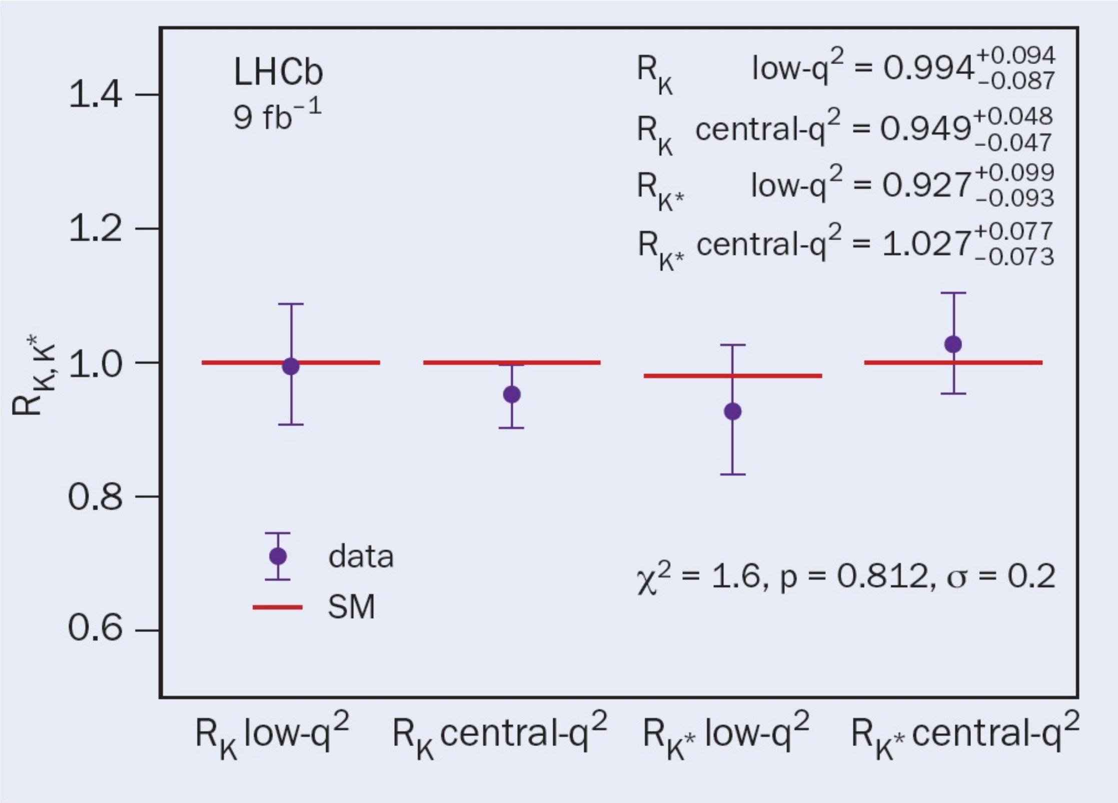
Figure credit: Scientific American



"Electroweak Penguin" "Box"

Possible breakdown of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, was reported in 2021.

https://arxiv.org/abs/2103.11769, And published in Nature



Alas, a mistake was found:

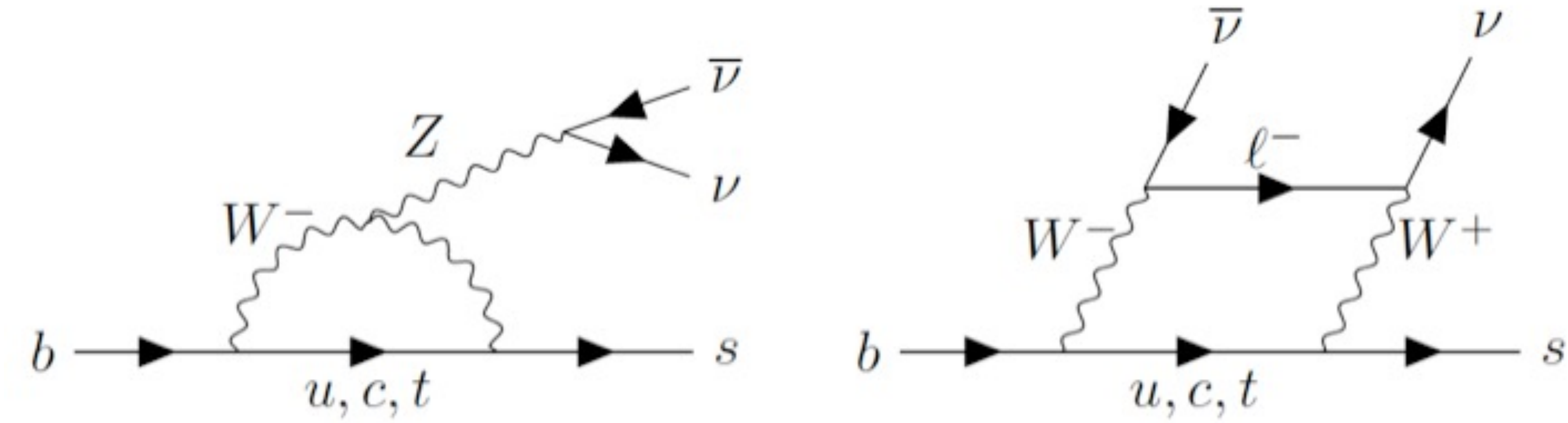
Details in https://arxiv.org/abs/2212.09153

Updated results with R_K *consistent with unity* published in PRL 131, 058013 (2023)

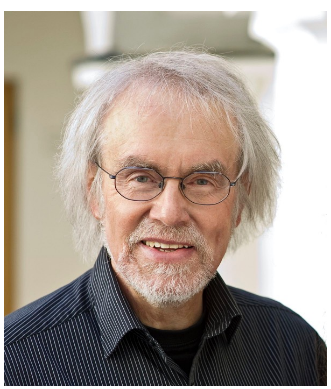
Still hints in angular asymmetries

"Although a component of this shift can be attributed to statistical effects, it is understood that this change is primarily due to systematic effects," explains LHCb spokesperson Chris Parkes of the University of Manchester. "The systematic shift in R(K) in the central q^2 region compared to the 2021 result stems from an improved understanding of misidentified hadronic backgrounds to electrons, due to an underestimation of such backgrounds and the description of the distribution of these components in the fit. New datasets will allow us to further research this interesting topic, along with other key measurements relevant to the flavour anomalies." –CERN Courier Dec 2022

$B \to K\nu\bar{\nu}$: BSM without hadronic uncertainties



(a) Penguin diagram (b) Box diagram



Andrezj Buras

Note that in contrast to B→K$^{(*)}$ l^+ l^- angular asymmetries, there are NO "dirty" long distance (charm annihilation) b→c cbar s contributions from B→J/ψ K$^{(*)}$ and B→ψ(2S) K$^{(*)}$

For example, https://arxiv.org/abs/1409.4557

The B→K$^{(*)}$ *ν νbar* missing energy modes are accessible to Belle II (and Belle), but might be difficult at a hadron experiment.

Signal: B→K ν ν

[Belle II reports a 3.5σ excess or "evidence"]

http://arxiv.org/abs/2311.14647 (submitted to PRD)

- **Signal candidate:**
  - an identified charged kaon that gives the minimal mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)

Event (pre-selection):
- $4 \leq N_{track} \leq 10$
- $E_{total} > 4$ GeV
- $17° < \vartheta_{miss} < 160°$

→ **BDT$_1$ (first filter):**
- 12 event-shape based kinematic variables

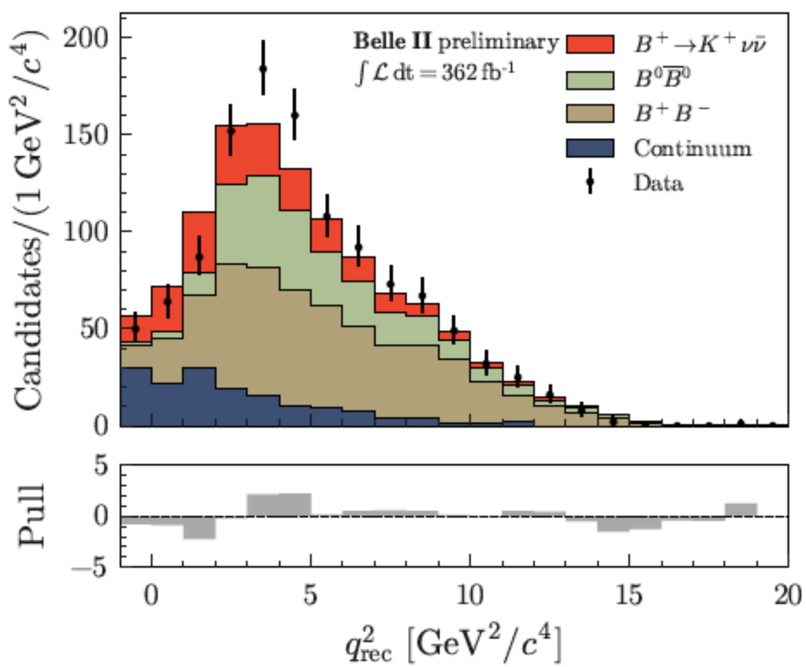
→ **BDT$_2$ (final selection):**
- *35 input variables*: using signal, event, and their correlations

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging. (X 10-20 ε compared to FEI, but large bkgs).

Now add on some ML/AI (boosted decision trees or BDTs) to help us tame the large backgrounds.

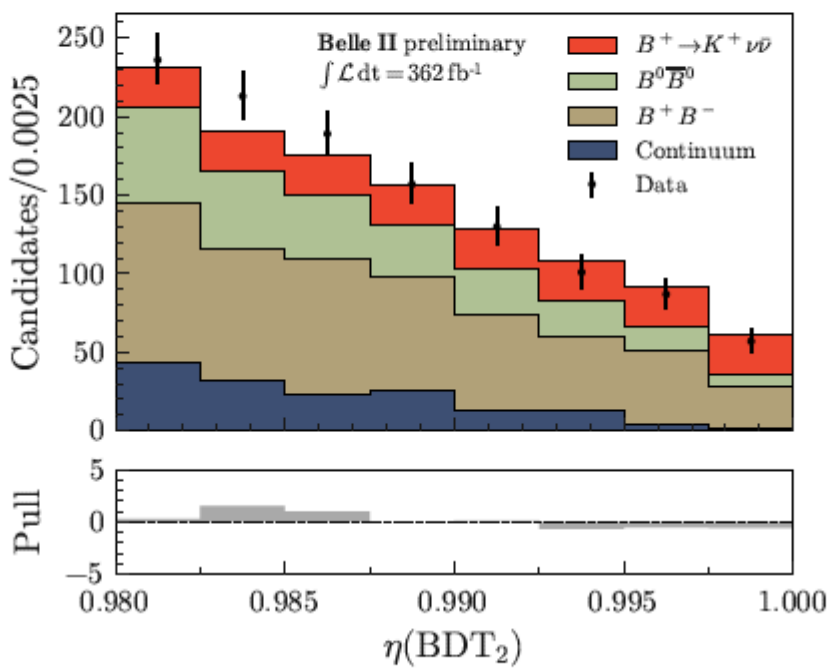
Fits in bins of BDT2 and q^2

Distributions for the signal-enhanced region in the ITA (Inclusive tagged analysis)

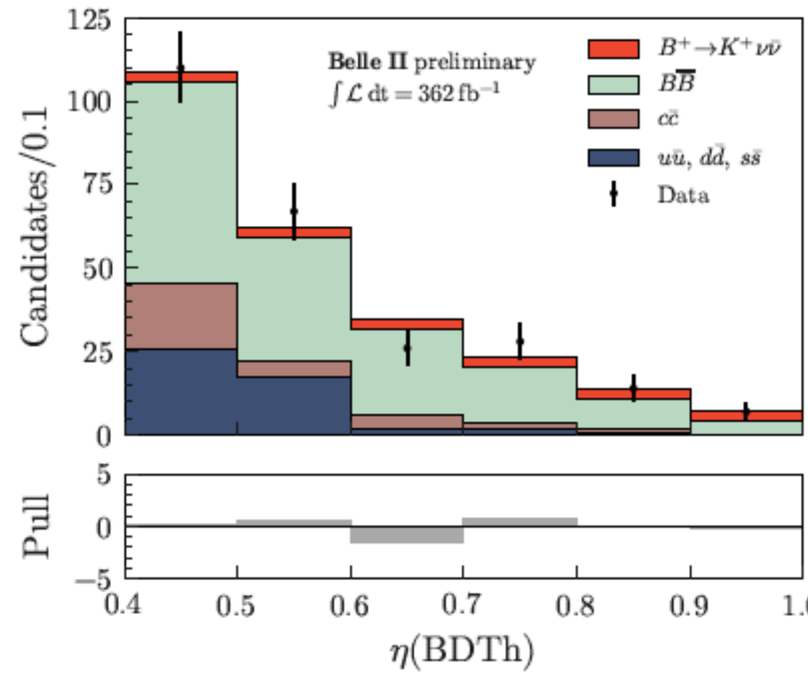


Signal: B→K ν ν

Inclusive tagged analysis

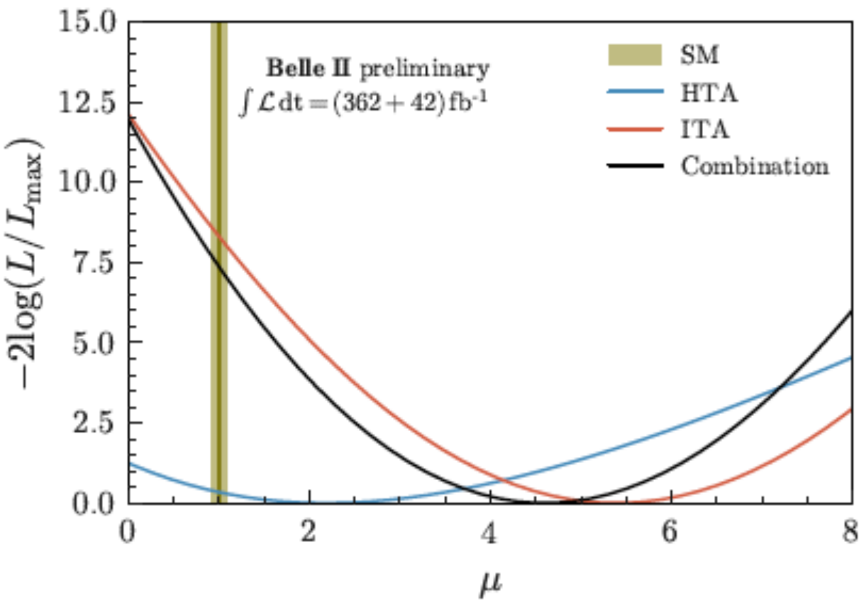


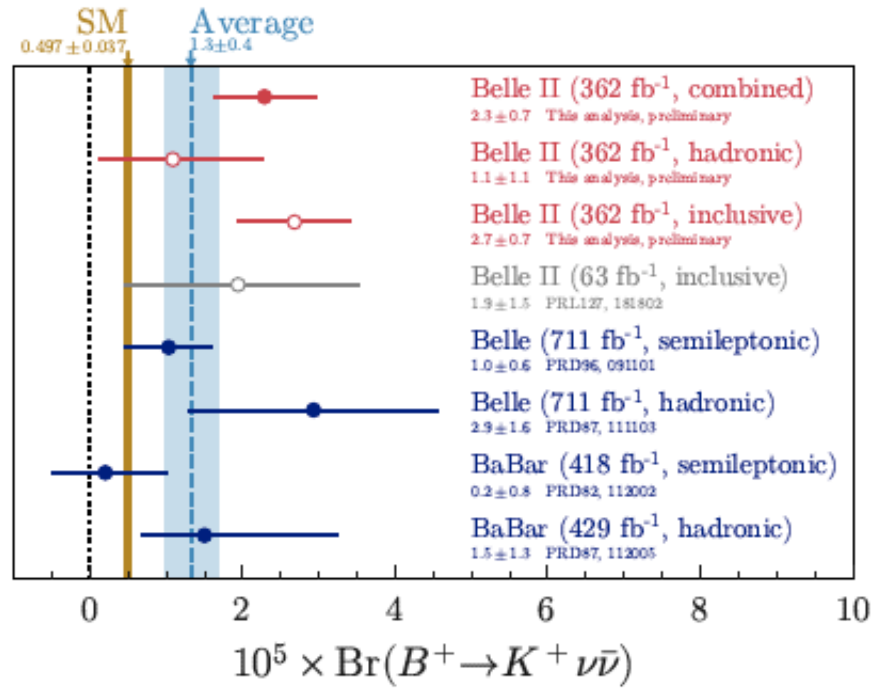
Consistency check with the lower sensitivity FEI hadronic tag.



B→K ν ν:

Combination and comparison
with other measurements.





BF(B→K $\nu\ \nu bar) = (2.3\ \pm 0.7) \times 10^{\{-5\}}$

Significance of signal excess is 3.5 standard deviations. The signal is 2.7σ above the SM expectation.

B→K ν νbar: BSM without hadronic uncertainties

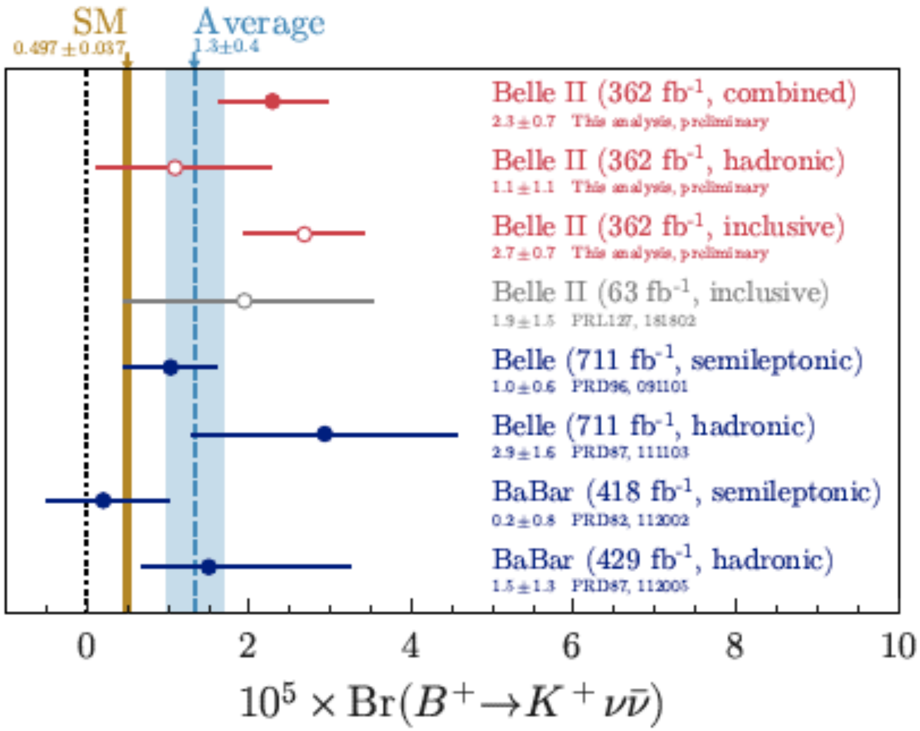
A new anomaly is emerging (now ~2.7σ from the SM)

$B \to K\nu\bar{\nu}$

New Technique from Belle II with inclusive ROE (Rest of the Event) tagging.

Phys. Rev. Lett. 127, 181802, (2021) and a consistency check with hadronic FEI.

Can now apply to old Belle data too.



It is quite possible that NP shows up in b→s nu nubar and not b→s l+ l- or vice-versa.
Maybe third generation couplings b->s $\tau^+\tau^-$ are enhanced

Dark matter could also play a major role.

>>>This is one way that Belle II could discover BSM Physics soon <<<

Potential for BSM Discoveries with Belle II@SuperKEKB/ "Take home or Apres ski" message

Quantum mechanics, entanglement, symmetry and *symmetry breaking* are at the heart of the particle physics in Belle II

- Belle II is exploring BSM Physics on the Luminosity or Intensity Frontier. *This is different from the LHC high pT program*

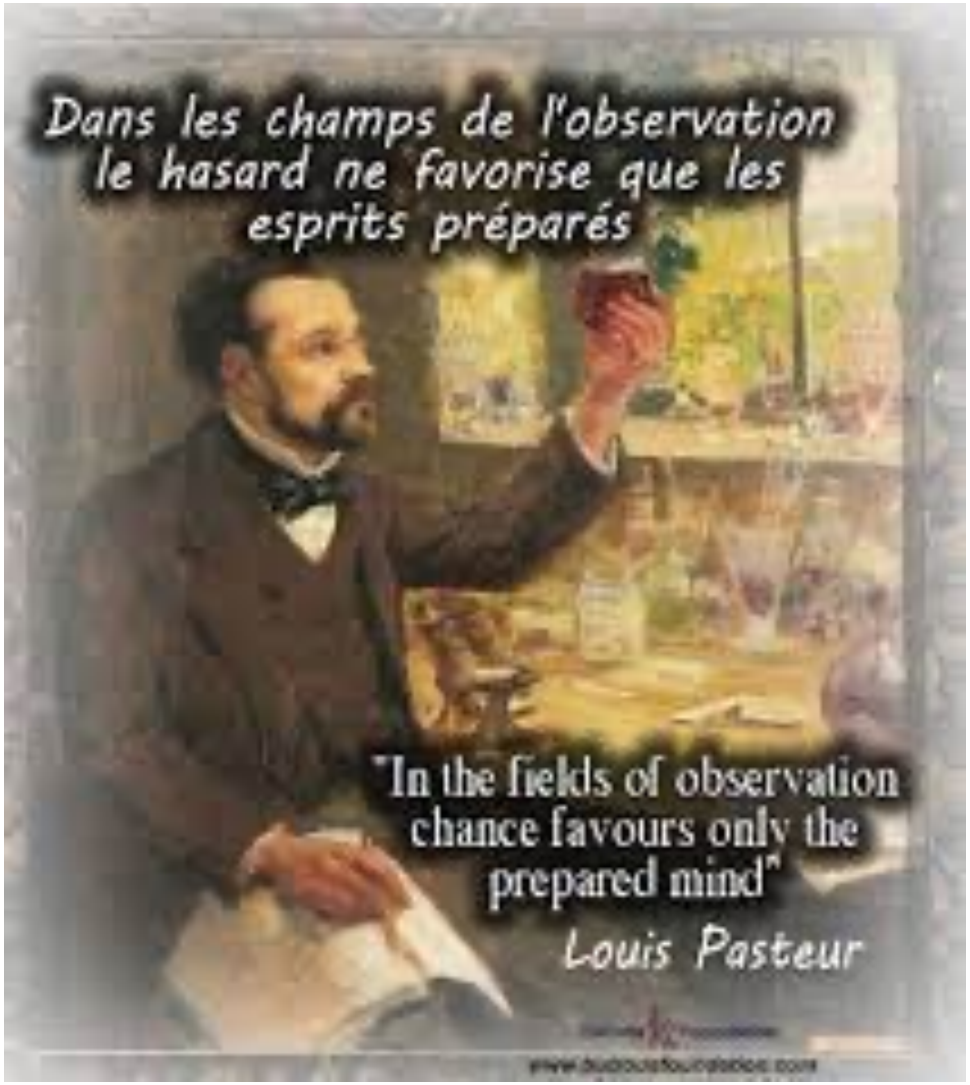
- *Hints of BSM physics in* $B \rightarrow K\nu\bar{\nu}$ *(start of a program)*

What's next, going beyond $R_{K,}$ (see the backup),
angular asymmetries in $B \rightarrow K^* l+ l-$ and $B \rightarrow D^* l \nu$???

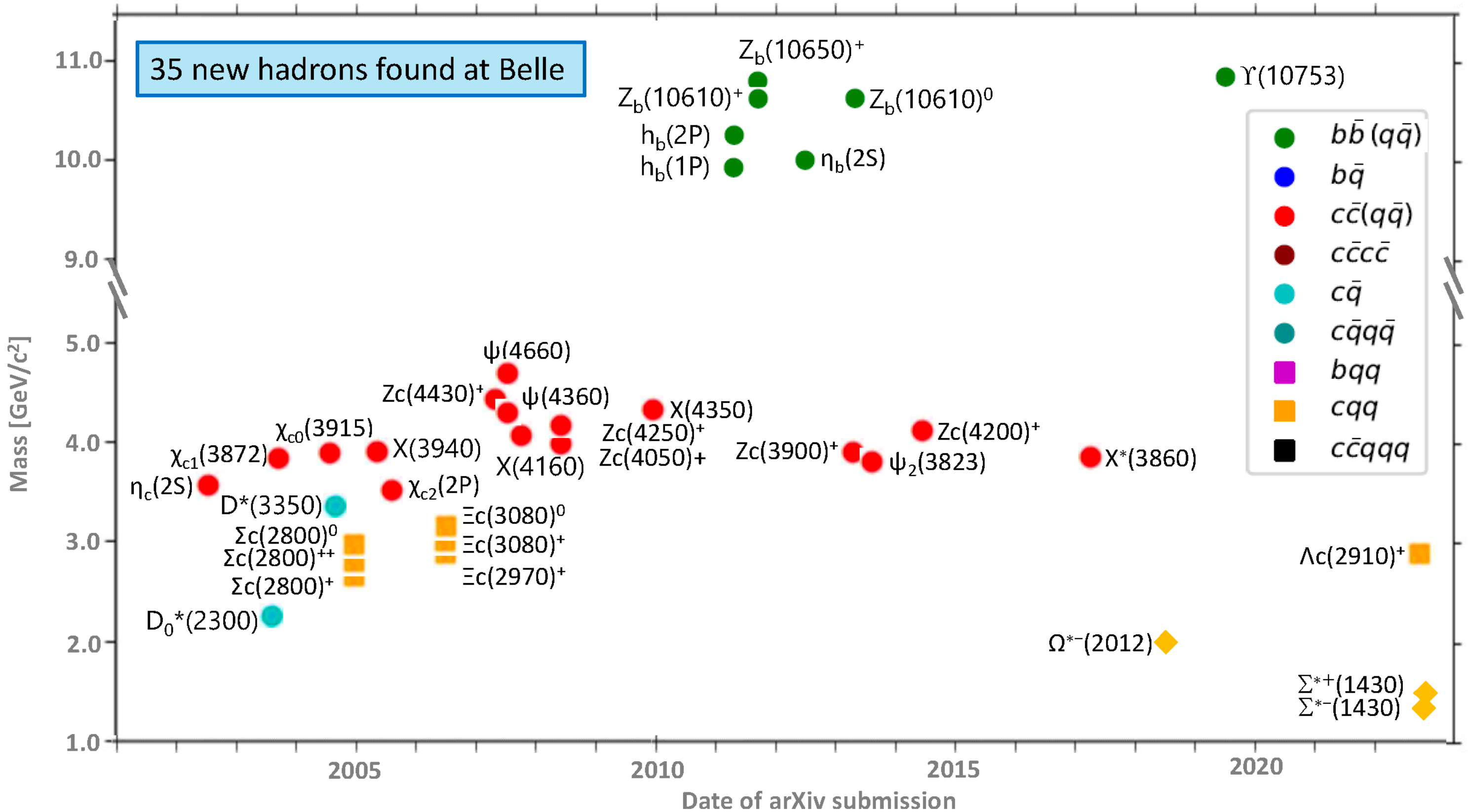
Chiral Belle: add e^- polarization to SuperKEKB (see the backup)

Strong interactions (more backup):
Belle II results on new hadrons with b bbar quarks (10.75 GeV scan)
Measurements relevant to the g-2 mystery e.g. $\sigma(e^+ e^- \rightarrow \pi^+ \pi^-)$

Backup slides



New Particles at Belle (and being investigated at Belle II)



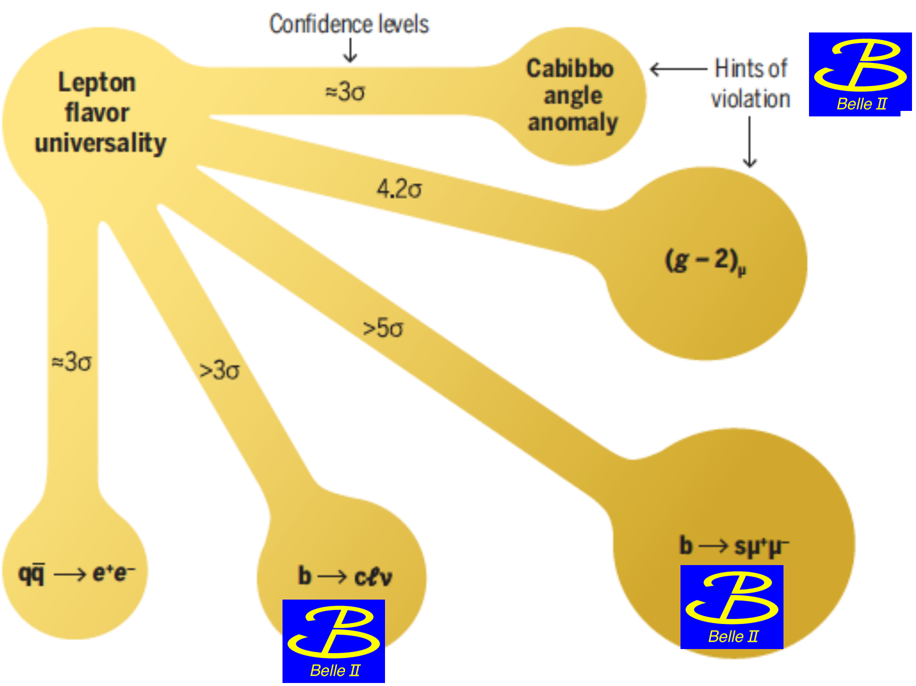
35 new hadrons were found at Belle. 10 of these are "exotic" and cannot be explained in the conventional quark model while the nature of 8 of them are still under investigation. The remaining 17 states are consistent with the quark model. Measurements of all these states will provide critical insights for QCD.

But wait there's more…..

Belle II can contribute to the resolution of the Cabibbo Angle Anomaly (CAA)

Possible violations of lepton flavor universality are getting harder to ignore

Shown are five hints for the violation of lepton flavor universality from existing experimental data, with the size of each circle and length of each arm reflecting the level of confidence for the experimental data to break away from standard model predictions.

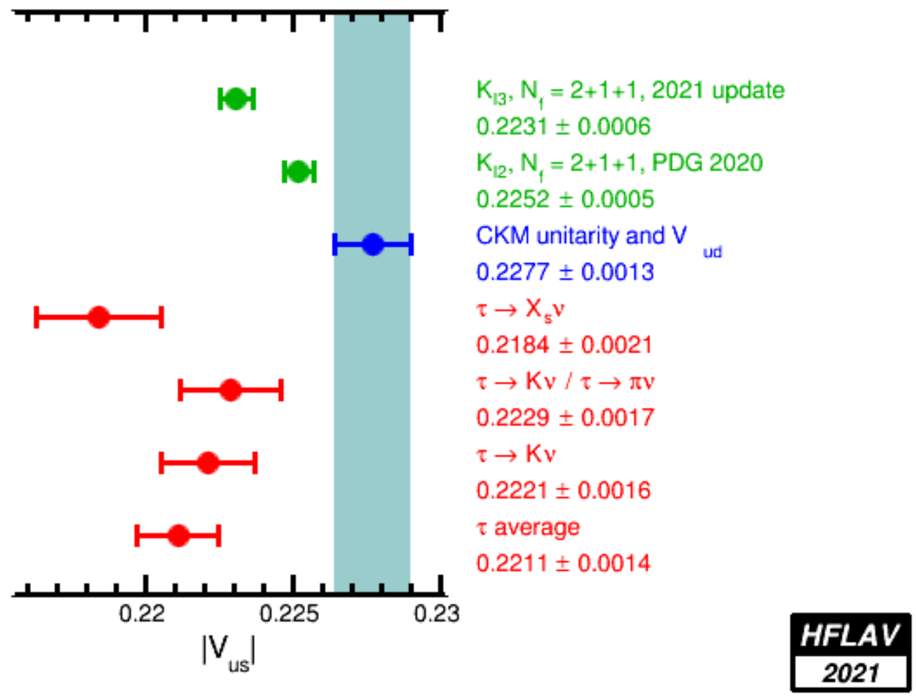


From December 2021 SCIENCE magazine article by A. Crivellin and M. Hoferichter.

A major supporting role of Belle II in the resolution of two more of the other HEP anomalies.

There is a ~3σ discrepancy between $|V_{us}|$ measured from tau and kaon semileptonic decays.

Belle II will measure $|V_{us}|$ in inclusive tau decays to high precision



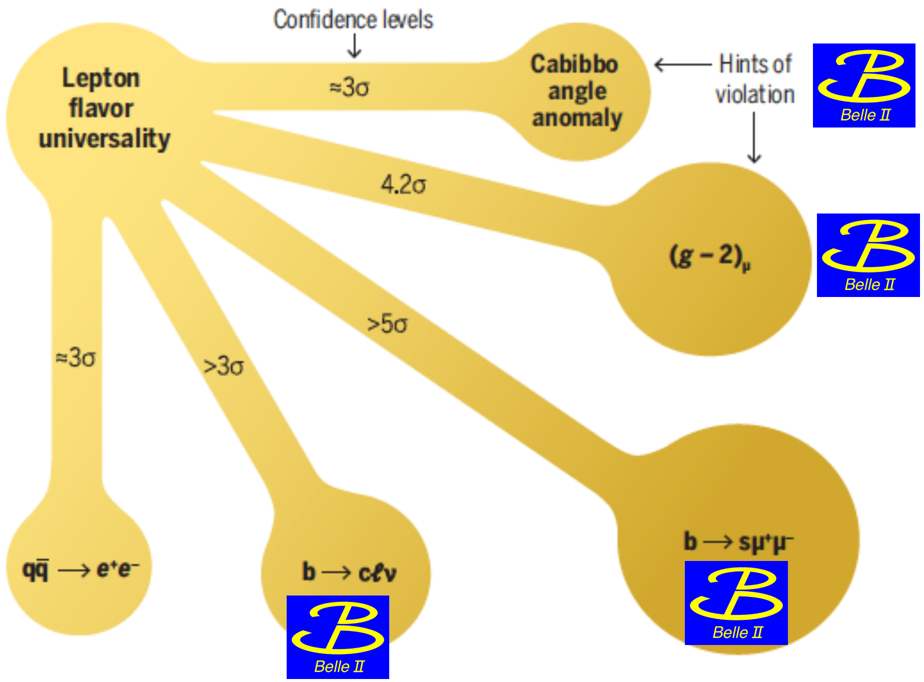
The CAA could be another hint of lepton flavor universality violation

+But wait there's still more…..

Belle II can contribute to g-2

Possible violations of lepton flavor universality are getting harder to ignore

Shown are five hints for the violation of lepton flavor universality from existing experimental data, with the size of each circle and length of each arm reflecting the level of confidence for the experimental data to break away from standard model predictions.



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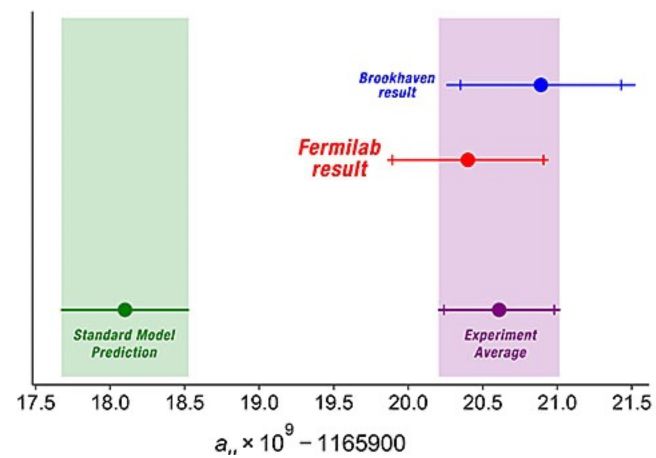
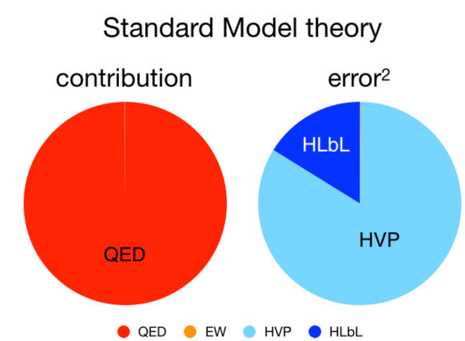




KLOE and BaBar, CMD3 data disagree

Belle II can measure the cross-section for $e^+e^- \rightarrow \pi\pi$ vs sqrt(s) and reduce the hadronic vacuum polarization error in g-2 (dominant theory uncertainty). This could help to determine whether there really is BSM Physics in g-2 (muon).

Belle II sensitivities to B→K(*) nu nubar at Snowmass

Snowmass proceedings: https://arxiv.org/abs/2207.06307

Table 3: Baseline (improved) expectations for the uncertainties on the signal strength μ (relative to the SM strength) for the four decay modes as functions of data set size.

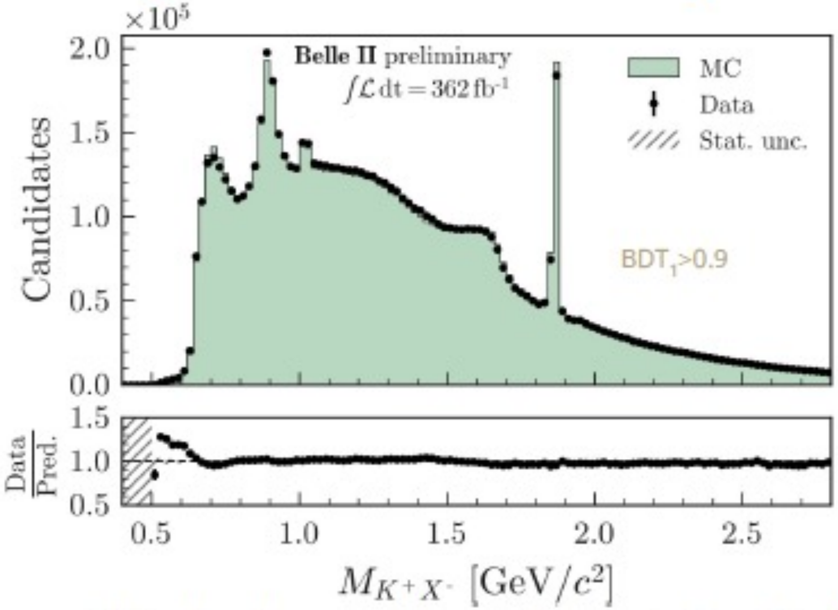
Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

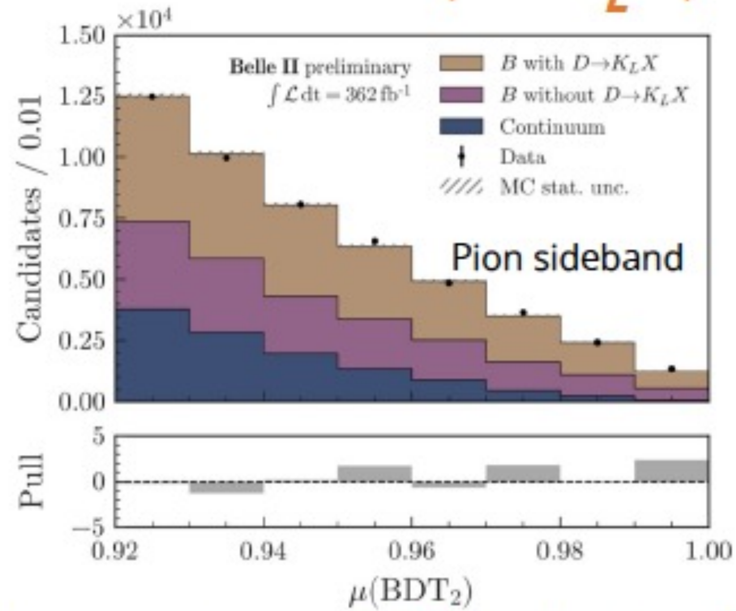
higher signal efficiency and better sensitivity than any previous approach, as shown by the Belle II $B^+ \to K^+\nu\bar{\nu}$ branching fraction results [80].

Program: In the future, Belle II should be able to measure B→K nu nubar, K* nu nubar, q^2 spectra and K* polarization.

Main backgrounds

Background from $B \to D(\to K^+ X) l\nu$ and $B \to K^+ D(\to K_L X)$

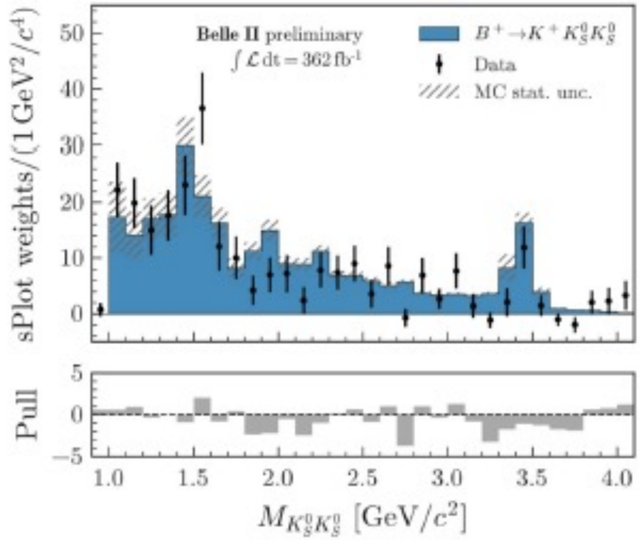




- Main backgrounds: semileptonic $B \to D(\to K^+X)l\nu$ decays and prompt $B \to K^+X$ production (>90%)
- Semileptonic decays suppressed by several MVA variables, checked at each selection step
- Prompt K^+ production studied using prompt π^+ from $B^+ \to \pi^+ X$ (and l^+ from $B^+ \to l^+ X$) decays
- Systematic uncertainties on decay branching fractions, enlarged for $D(\to K_L X)$ and $B \to D^{**} l\,\nu$

Background from $B^+ \to K^+ K^0 K^0$

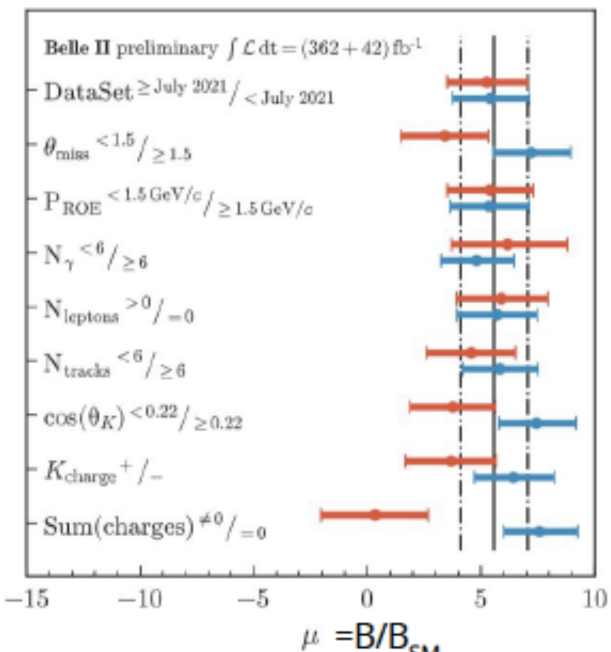
Most signal-like backgrounds

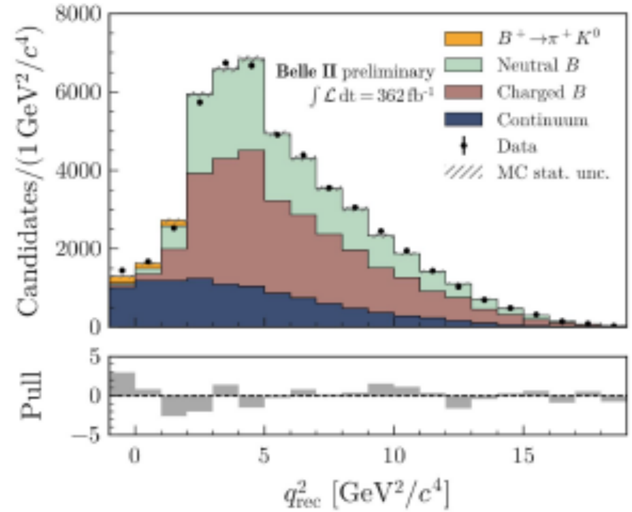


$\leftarrow B^+ \to K^+ K_S K_S$ decays

- Backgrounds from $B^+ \to K^+ nn$ and $B^+ \to K^+ K^0 K^0$ have branching fractions of few x 10^{-5}, however K_L and neutrons can escape EM calorimeter
- $B^+ \to K^+ K^0 K^0$ modeled based on BaBar analysis (arXiv:1201.5897)
- Dedicated checks of K_L performance in calorimeter using radiative φ production
- Dedicated checks using $B^+ \to K^+ K_S K_S$ and $B^0 \to K_S K^+ K^-$ control channels

Cross checks





$B(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

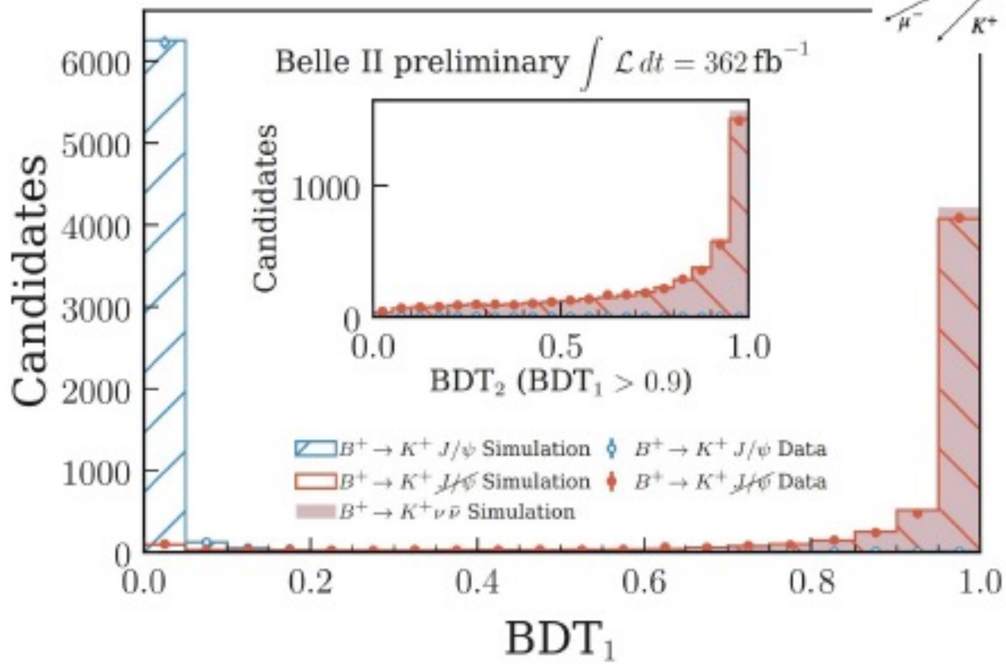
PDG: $(2.38 \pm 0.08) \times 10^{-5}$

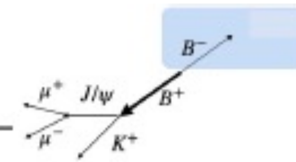
- Multiple checks of the analyses stability, including tests dividing data into approximately equal sub-samples. Reported here as measured branching fraction divided by SM expectation, μ=B/B$_{SM}$.
- Control measurement of $B^+ \to \pi^+ K^0$ decay

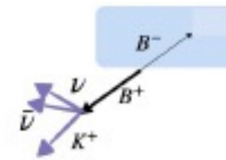
Systematic uncertainties of the inclusive analysis

Source	Correction	Uncertainty type	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2 NP	50%	0.88
Normalization of continuum background	—	Global, 5 NP	50%	0.10
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	$+30\%$	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	0.05
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.08
Hadronic energy scale	-10%	Shape, 1 NP	10%	0.36
K^0_L efficiency in ECL	-17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
MC statistics	—	Shape, 156 NP	$O(1\%)$	0.52

Signal efficiency validation



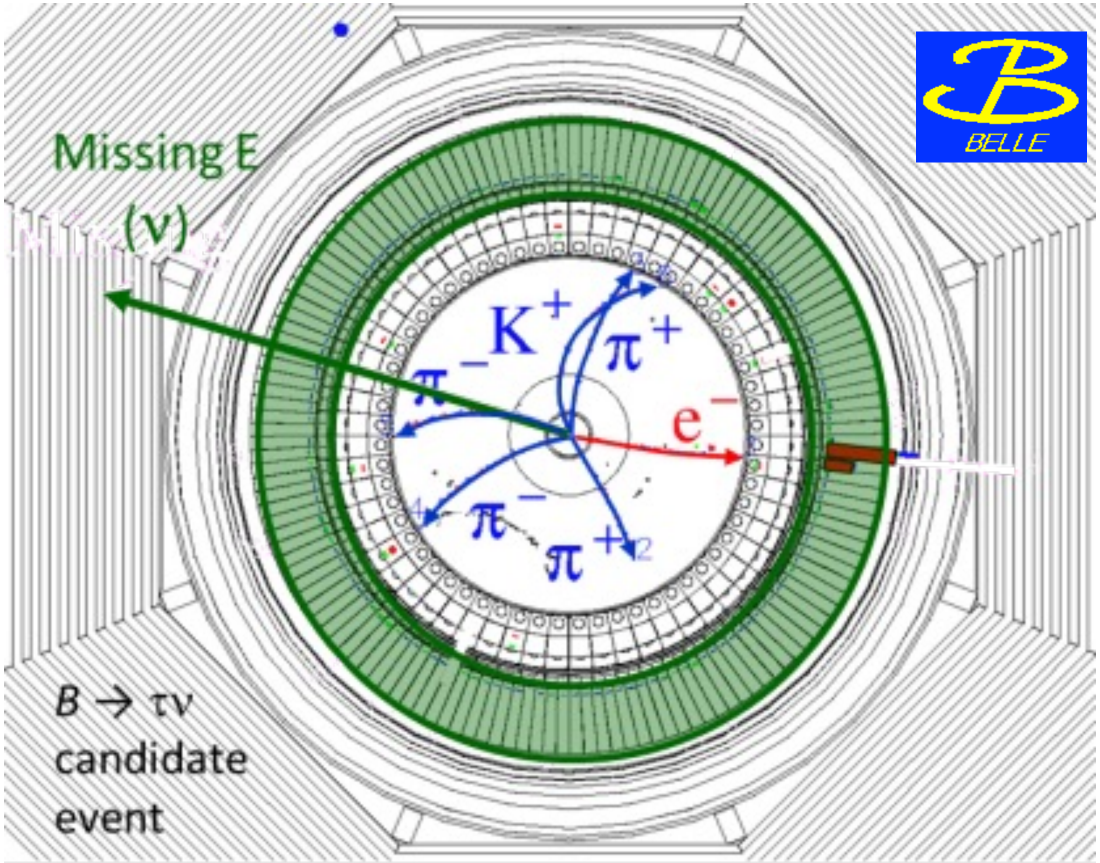




- Use cleanly reconstructed $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ decays with $\mu^+\mu^-$ pair removed and K^+ kinematics adjusted to validate the signal efficiency in simulation. The ratio of data/simulation efficiency in the signal region is **1.00±0.03**

Example of a Missing Energy Decay ($B \to \tau\nu$) *in old Belle Data* (recorded before 2010)

$$B^+ \to \overline{D}^0 \pi^+$$
$$(\to K\pi^-\pi^+\pi^-)$$
$$B^- \to \tau(\to e\nu\bar{\nu})\nu$$



The clean e^+e^- environment (and the CsI(Tl) crystal calorimeter) makes this possible.

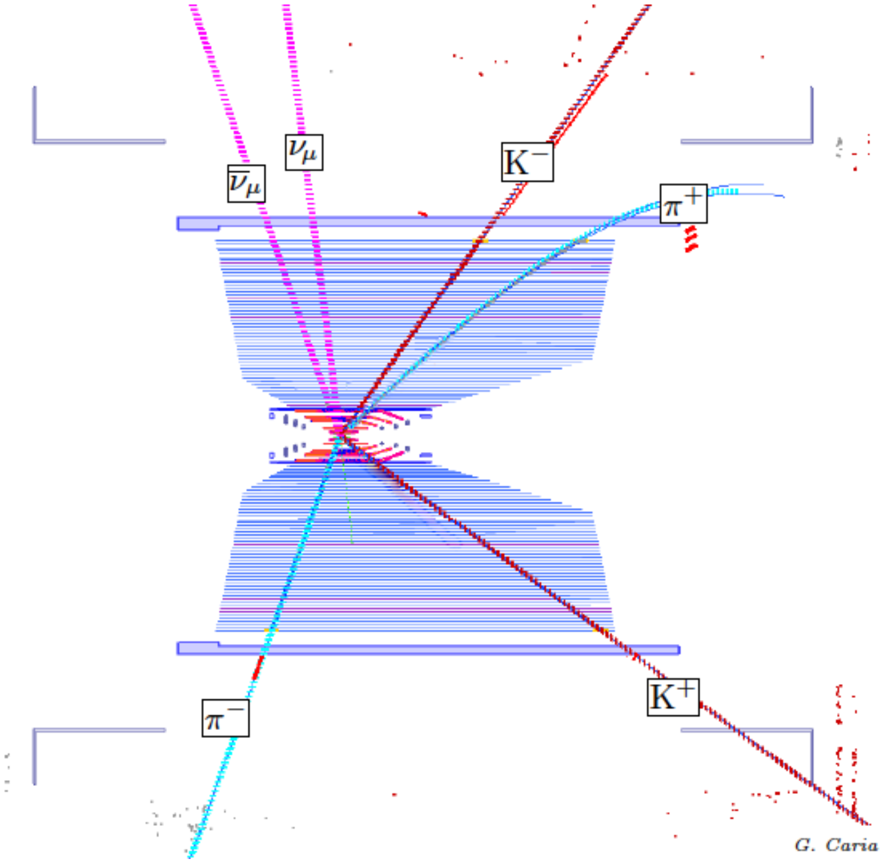
Realizing "Buras' clean dream" in Belle II ?

"Missing Energy Decay" in a Belle II GEANT4 MC simulation

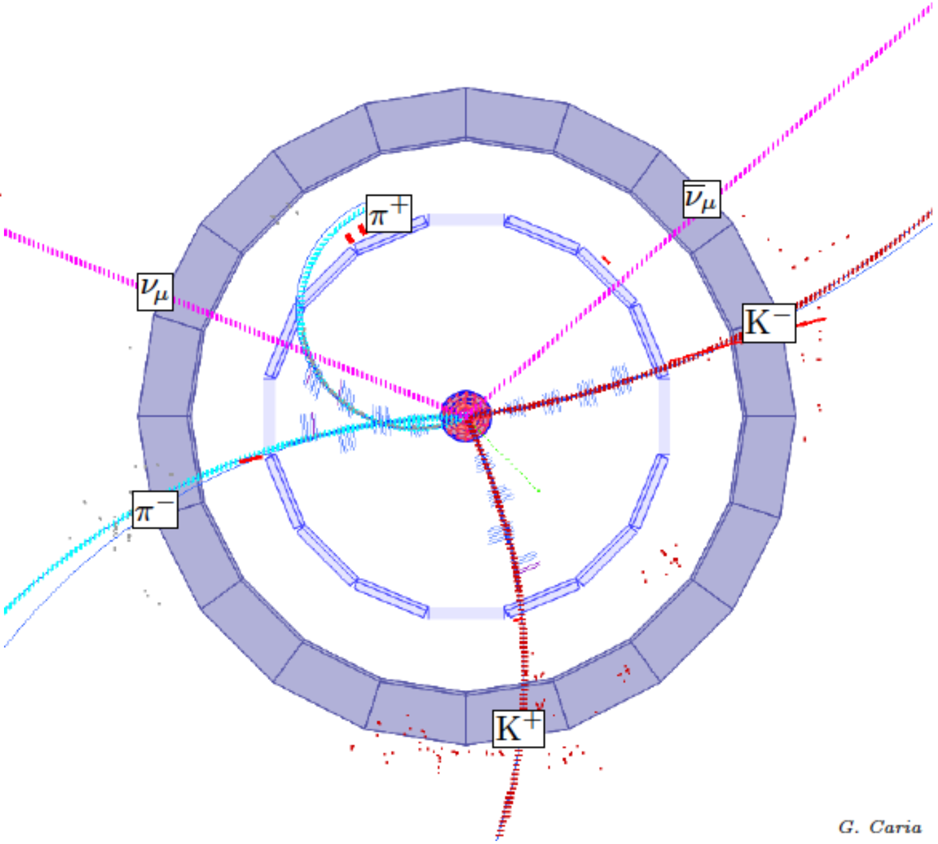
Signal: B→K ν ν

tag mode: B→Dπ; D→Kπ

View in r-z

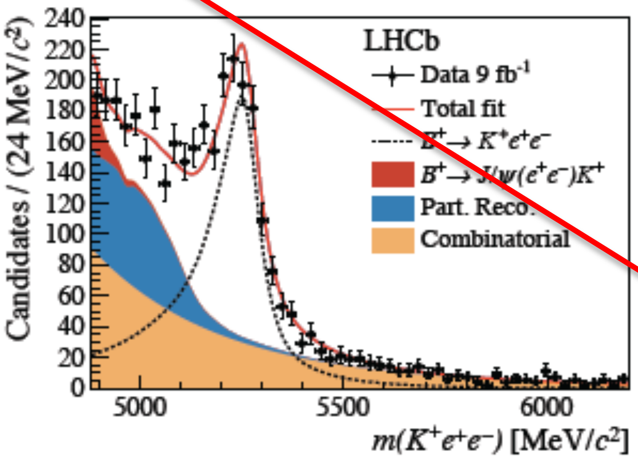


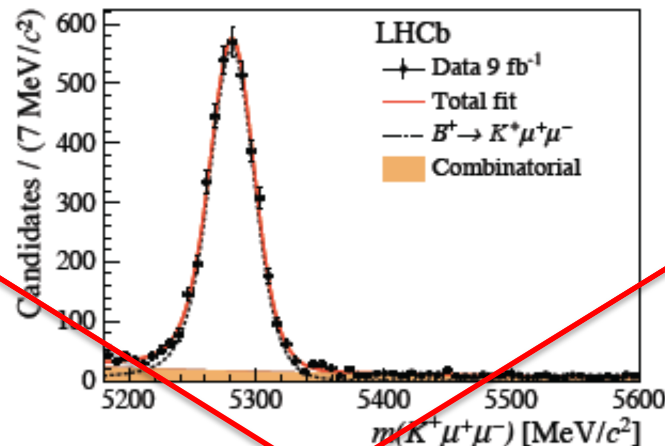
Zoomed view of the vertex region in r--phi

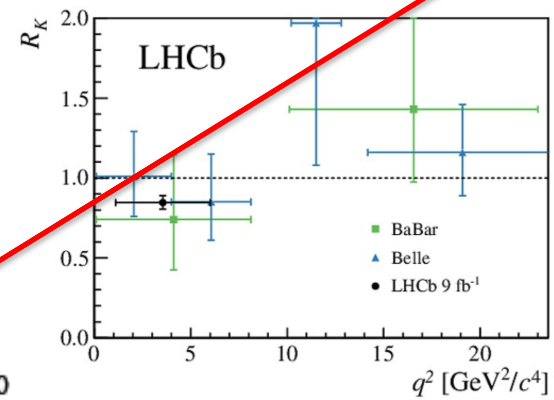


Possible breakdown of Lepton Universality in b→s l+ l- transitions by the LHCb experiment at CERN, reported in 2021.

https://arxiv.org/abs/2103.11769, published in Nature







$$R_K = \frac{BF(B^+ \to K^+\mu^+\mu^-)}{BF(B^+ \to J/\psi(\to \mu^+\mu^-)K^+} \Big/ \frac{BF(B^+ \to K^+e^+e^-)}{BF(B^+ \to J/\psi(\to e^+e^-)K^+}$$

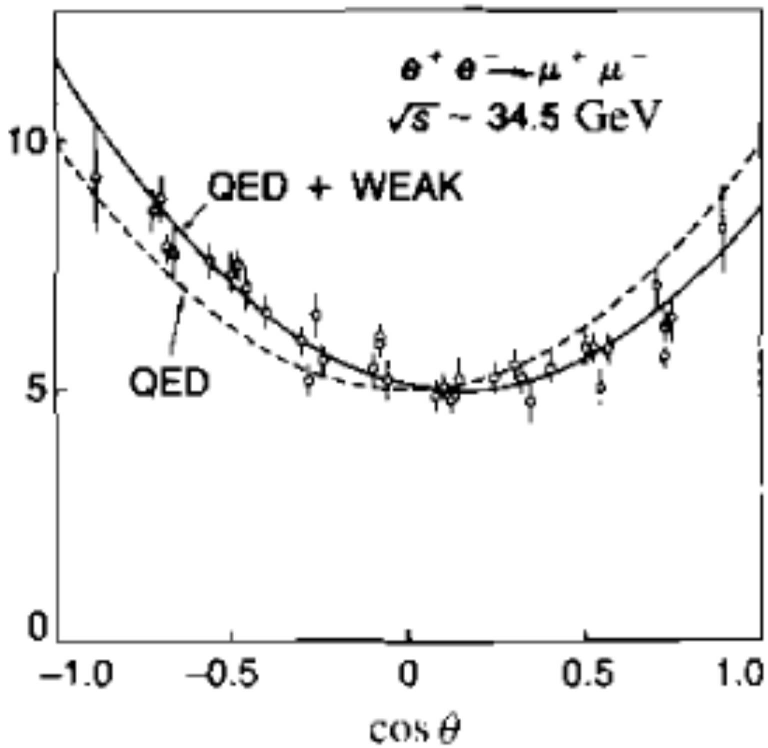
$$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/\mathrm{c}^4) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

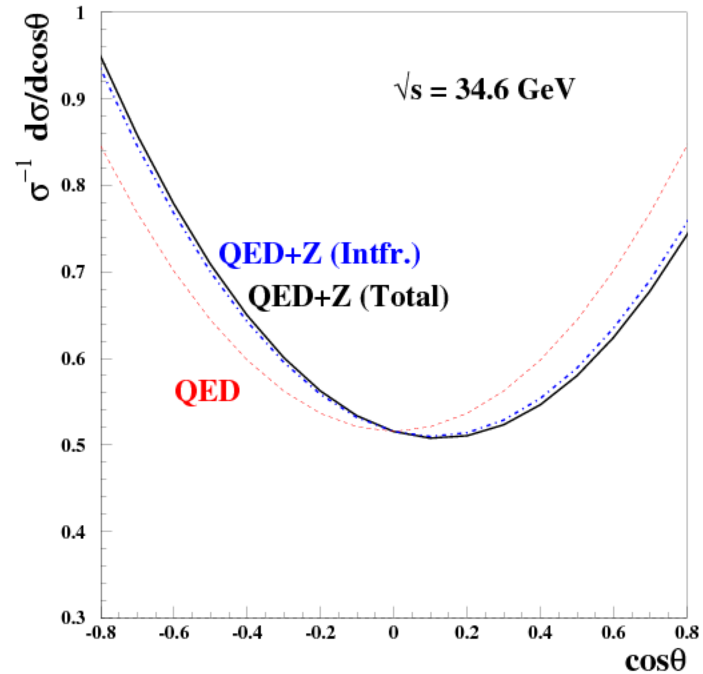
<1 (lepton universality prediction)

And thus this *might indicate* the breakdown of the Standard Model of Particle Physics (3.1 σ)

Note: $q^2 = M^2(l^+\ l^-)$

High Energy Physics History: finding NP in A_{FB} (using interference)





Conclusion from this angular distribution: There is a Z boson at higher energy even though colliders of the time did not have enough $\sqrt{s}$ to produce it ($|A|^2 + |B|^2 + 2\,A^* B$)

Time for a shift in thinking: (after R_K disappeared)

Look for lepton universality violation in
$B \to K^* l^+ l^-$ (and $B \to D^* l \nu$) angular distributions
or b→s nu nubar.

Use "Delta" Δ observables (comparing electron and muon angular distributions) to fit for BSM Wilson coefficient contributions
https://arxiv.org/abs/2203.06827

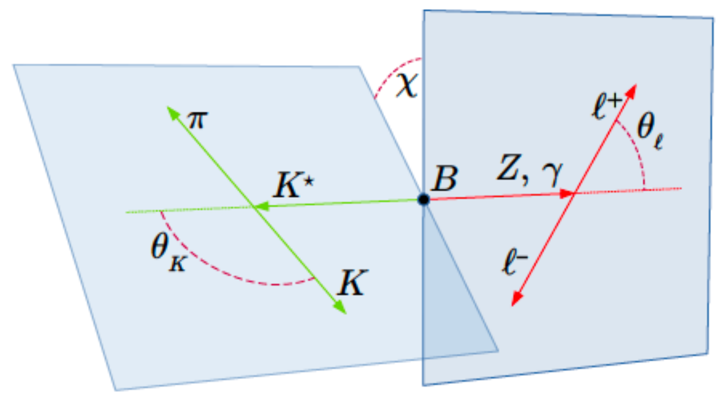


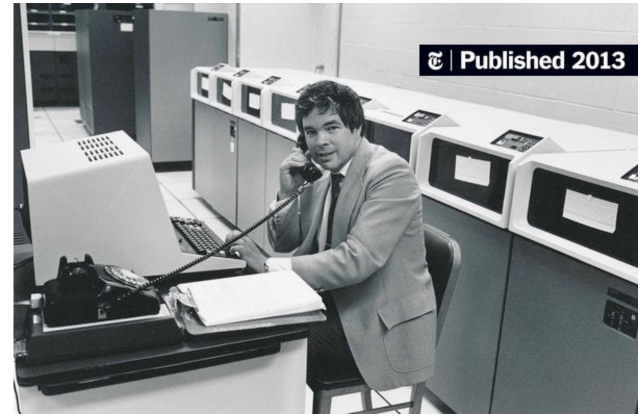
FIG. 1. The $B \to K^* \ell^+ \ell^-$ decay and the subsequent $K^* \to K\pi$ decay kinematic parameters.

Equally strong detection capabilities for electrons and muons. Already publishing a number of lepton universality tests. Ideally suited for this mission but large Belle II datasets are needed.

Feynman Diagrams and Model Building

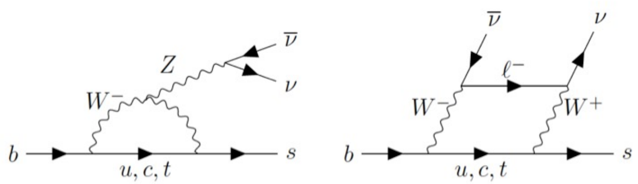
Effective Field Theory
→Wilson Coefficients

Paradigm shift



Feynman family and diagrams

Ken Wilson ("Wilson coefficients")



(a) Penguin diagram (b) Box diagram

C_7, C_9, C_{10}

New Physics/BSM Couplings in b→s

The effective Hamiltonian for $b \to s$ transitions can be written as

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

and we consider NP effects in the following set of dimension-6 operators,

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}' = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,.$$

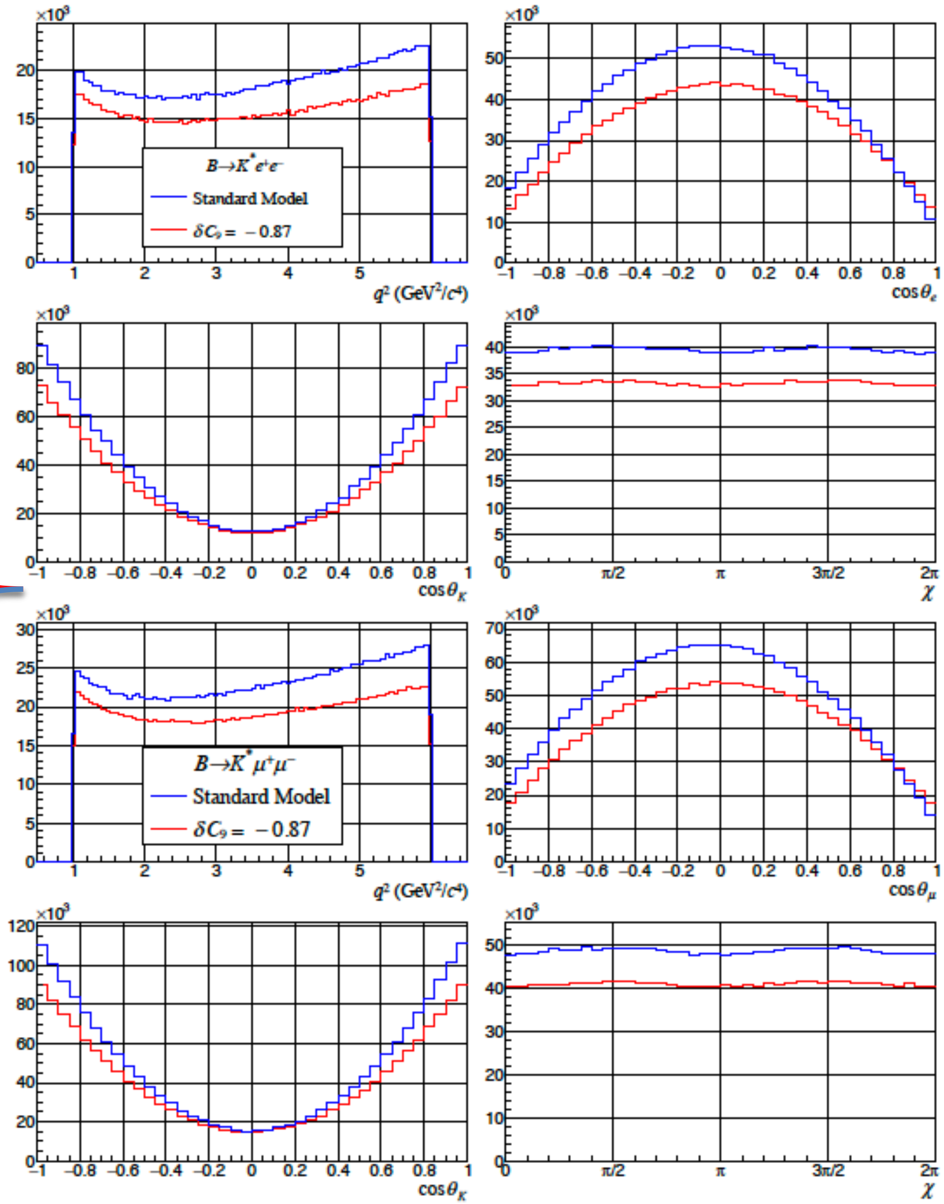
The primes are NP right-handed couplings.

MC $B \to K^*$ l+ l- @Mid q^2 ([1-6] GeV^2): dielectrons vs dimuons

dielectrons

Now the effects in di-electrons and dimuons are similar

dimuons



Hunting for

$$\delta C_9 = -0.87$$

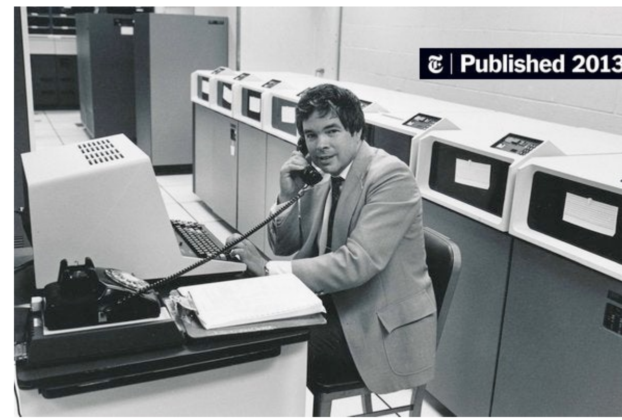
Multiple differences in angles and q^2

We need new tools to explore BSM physics couplings

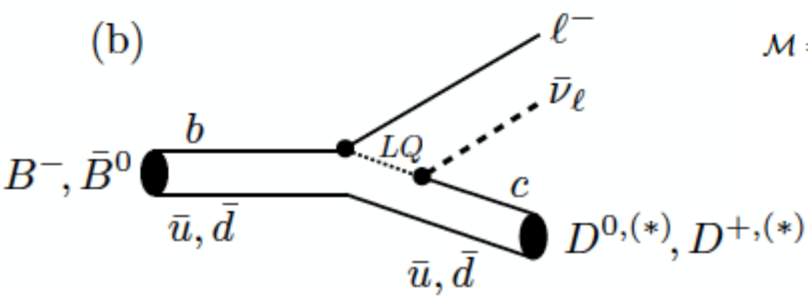
Monte Carlo Generators for B→D* l nu and B→K* l+ l- that allow for SM and BSM physics in Wilson coefficients. This will allow for new and powerful experimental analyses of angular dependences.

Feynman and his diagrams

Paradigm shift



Wilson and his Coefficients in Effective Field Theories



$$\mathcal{M} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big\{ \langle D\pi | \bar{c}\gamma^\mu \left[(1+g_L)P_L + g_R P_R\right] b | \overline{B} \rangle (\bar{\ell}\gamma_\mu P_L \nu) + \langle D\pi | \bar{c}(g_{S_L} P_L + g_{S_R} P_R) b | \overline{B} \rangle (\bar{\ell} P_L \nu) + g_T \langle D\pi | \bar{c}\sigma^{\mu\nu} b | \overline{B} \rangle (\bar{\ell}\sigma_{\mu\nu} P_L \nu) \Big\}$$

Can now MC this matrix element for any value of g_L, g_R, g_{SL}, g_{SR}

Potential for BSM Discoveries with Belle II@SuperKEKB/ "Take-home message"

Quantum mechanics, entanglement, symmetry and *symmetry breaking* are at the heart of the particle physics in Belle II

- Belle II is exploring BSM Physics on the Luminosity or Intensity Frontier. *This is different from the LHC high pT program*
- *Hints of BSM physics in B→K ν ν bar (start of a program)*

What's next:

angular asymmetries in B→K l+ l- and B→D* l nu ???*

Belle II Executive Summary for Snowmass (high energy physics for the next decade) https://arxiv.org/abs/2203.10203

Some new ideas/programs for BSM discoveries at Belle II
https://arxiv.org/abs/2107.01080 (published in PRD)
https://arxiv.org/abs/2203.06827 (submitted to JHEP)
https://arxiv.org/abs/2206.11283 (published in PRD)

Revisionist History and Paradigm Shift

The B factory experiments, Belle and BaBar, discovered large CP violation in the B system in 2001, compatible with the SM and provided a large range of CKM measurements. These provided the experimental foundation for the 2008 Nobel Prize to Kobayashi and Maskawa.

In the meantime, the LHC was constructed in 2008, ATLAS and CMS *completely changed* the nature of high energy physics. Of particular importance was the landmark discovery in 2012 of the Higgs boson.

This discovery was recognized by the 2013 Physics Nobel Prize to Englert and Higgs.

In addition, the high pT experiments, established tight constraints on direct production of high mass particles (e.g. M(Z'), M(W')>3 TeV, vector-like fermions > 800 GeV) and limits on SUSY. This *noble search* continues with the high luminosity LHC.

Paradigm shift: inspired by intriguing results from B factories, LHCb and the potential of Belle II, the possibility of finding BSM physics in quantum effects in flavor has emerged as a *alternate* route to going beyond the SM.

Younger theorists: Dark Sector may be another path.

At Snowmass in 2022, we explored the "Vision Thing" for Belle II/SuperKEKB

What happens at 50 ab^{-1} and beyond ?

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to K^{*0}\gamma)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

The dagger refers to a measurement in the range $1 < q^2 < 6$ GeV^2/c^2

JAHEP report to Snowmass: Arxiv 2203:13979

Consideration of further luminosity upgrade and electron polarization capability of SuperKEKB are started for ultimate new physics searches with heavy flavor quarks and leptons including τ lepton $g-2$ in the light of muon $g-2$ anomaly [28].

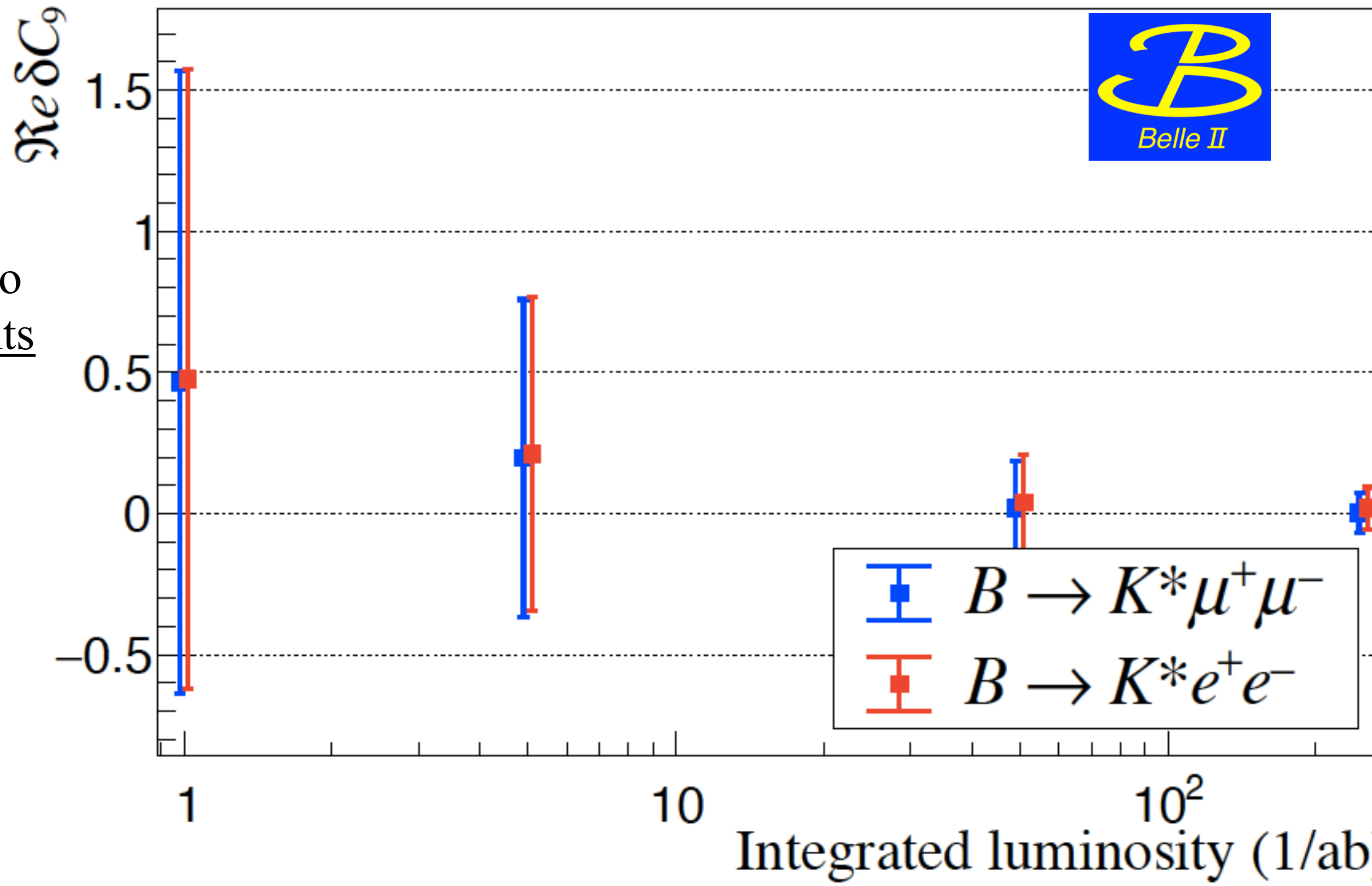
Backup slides on e- polarization and electroweak measurements.

Reminder and Motivation:

C_9 : Global fit to world b→s data still gives a deviation from the SM

What about the future ?

Estimates use pseudo-experiments with 4-D unbinned maximum likelihood fits to 4 variables in $B \to K^* l^+ l^-$ to extract Wilson coefficients C_i directly from data.



Use $q^2 > 1$ GeV^2 and $|q^2 - M^2| < 0.25$ GeV^2 and assume 25% Belle efficiency

A. Sibidanov et al.

https://arxiv.org/abs/2203.07189

Apres-Snowmass Bullet Point:
Use the Δ Observables in $B \to K^* l^+ l^-$ to discover New Physics at Belle II without QCD and hadronic uncertainties.

Work in progress

AI/ML and BSM Wilson coefficients

Idea: instead of 4-d max L fitting, convert the 4d distribution into an image and use CNNs to extract the BSM Wilson coefficient

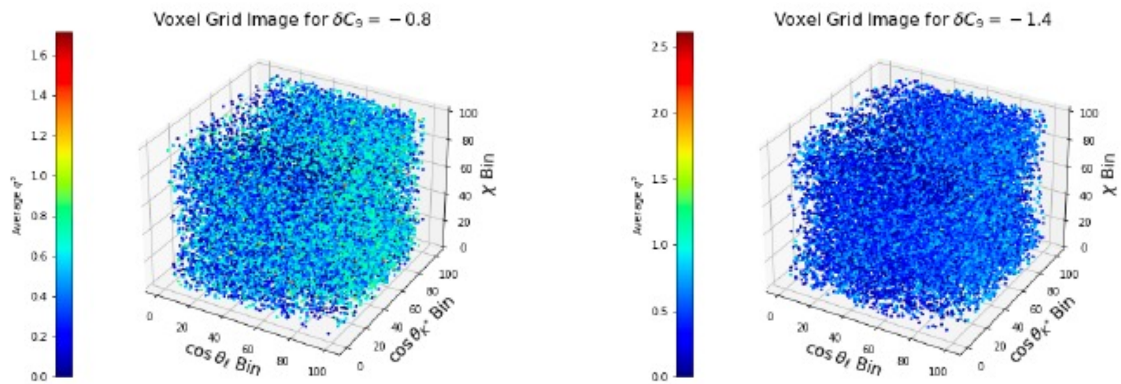
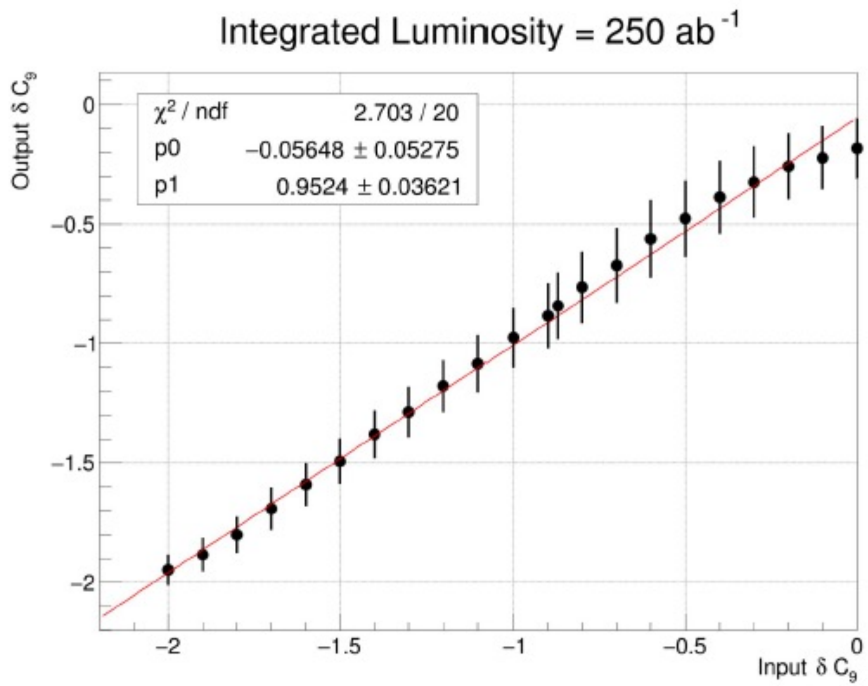


FIG. 8. The "images" of $B \to K^* \ell^- \ell^+$ angular observable data for two values of NP contributions to the operator C_9. Dubey and Browder are using a CNN (Convolutional Neural Net) to fit for δC_9 and BSM signals.

Technical point: Can add a background image from an Mbc sideband to the image.

Shawn Dubey et al.

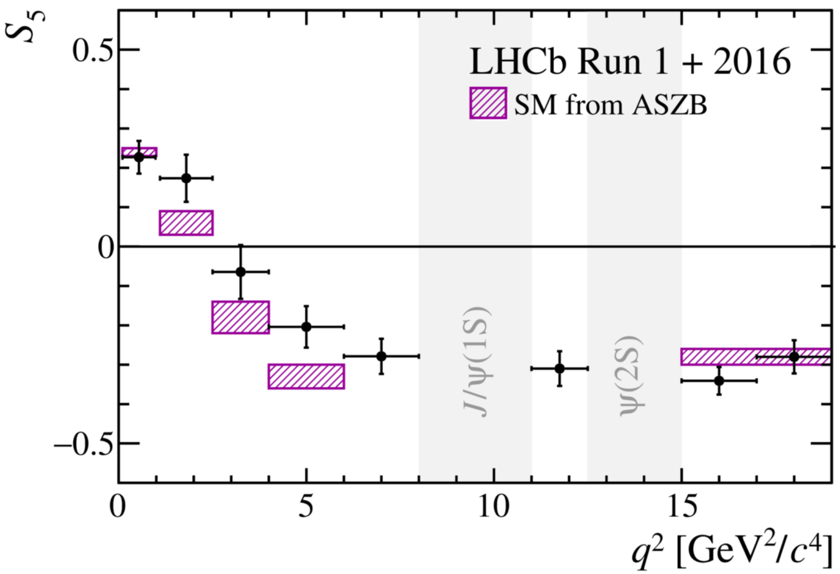


Regression via a convolutional neural network (CNN).

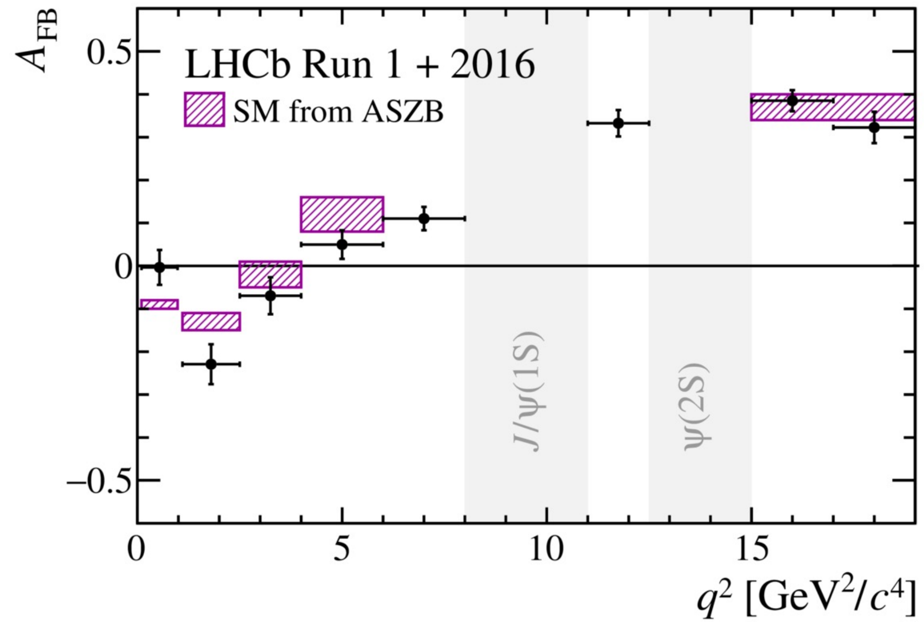
This is regression not classification (i.e. "dog vs cat")

Published LHCb 5 fb^{-1} results on $B \rightarrow K^* \mu^+\mu^- (q^2)$

A different angular asymmetry, involving χ



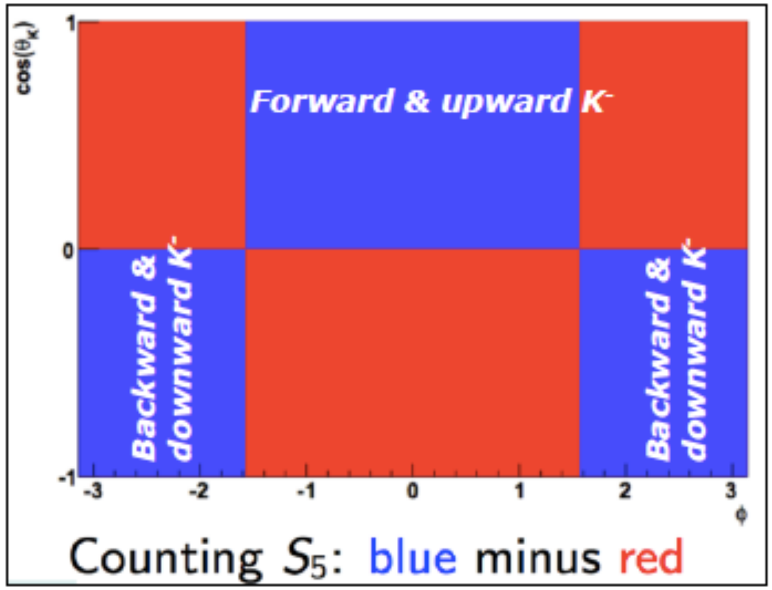
Forward-backwards asymmetry



"The P_5' measurements are only compatible with the SM prediction at a level of 3.7σ…..A mild tension can also be seen in the A_{FB} distribution, where the measurements are systematically <=1σ below the SM prediction in the region $1.1<q^2< 6.0$ GeV^2" (LHCb 2015 conference paper)

These angular asymmetries persist in 2023

More on angular asymmetries, A_{FB} , $S_5(q^2)$



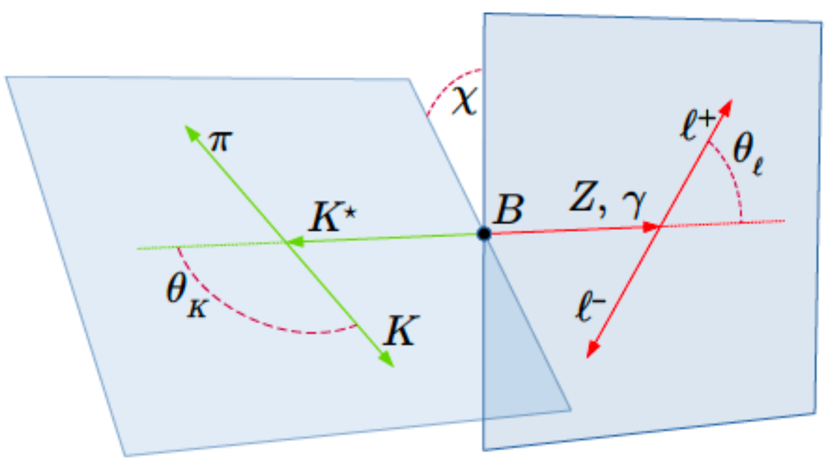
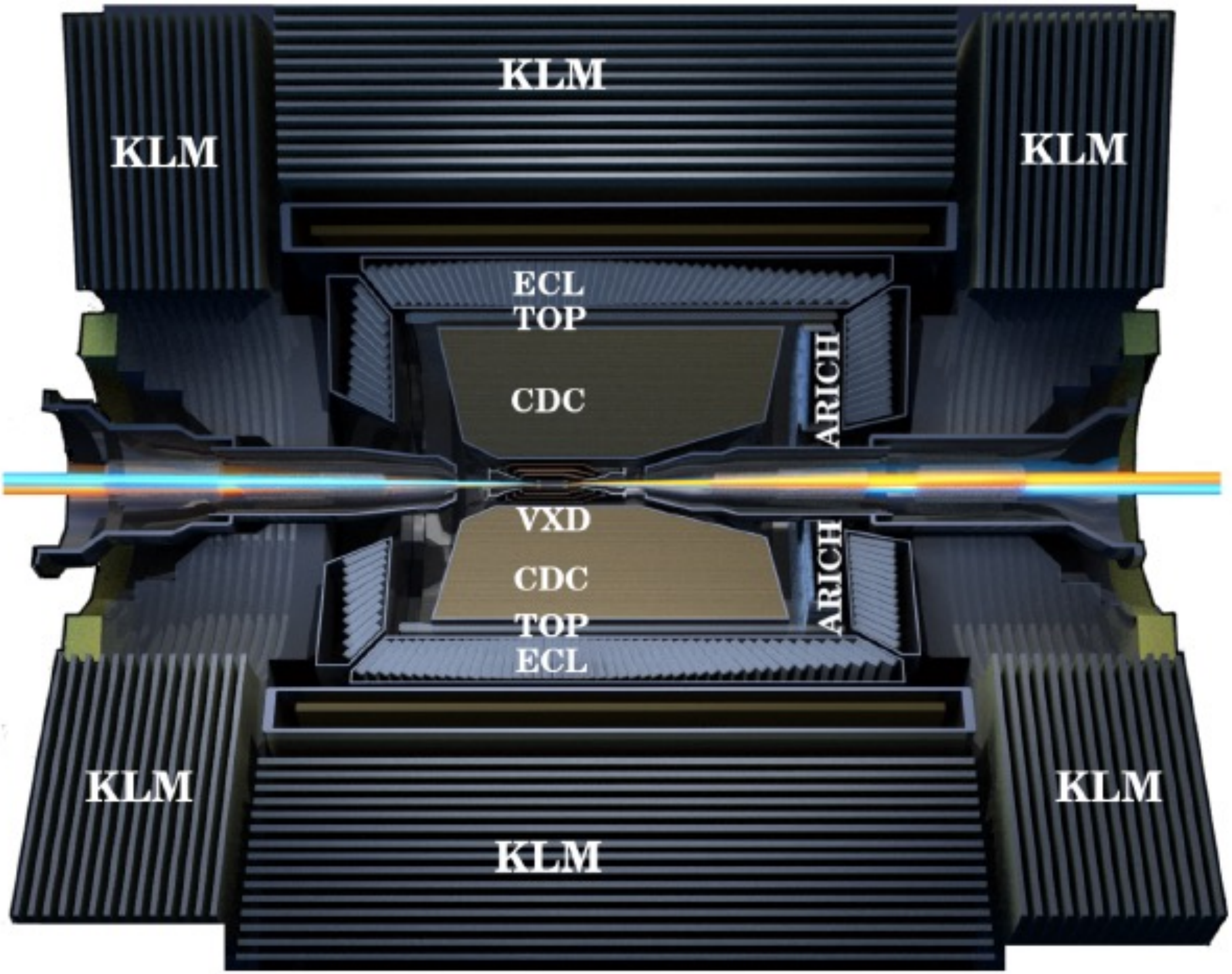


FIG. 1. The $B \to K^* \ell^+ \ell^-$ decay and the subsequent $K^* \to K\pi$ decay kinematic parameters.

Expect correlated angular asymmetries with sensitivity to BSM physics.

Cross-section of “Belle II in Black”



Chiral Belle Backup Materials

Upgrading SuperKEB with Polarized Electron Beams: "Chiral Belle" uses Belle II with L-R polarized SuperKEKB

- Goal is ~70% polarization with 80% polarized source (SLC had 75% polarization at the experiment)
- Electron helicity would be chosen randomly pulse-to-pulse by controlling the circular polarization of the source laser illuminating a GaAs photocathode (similar to SLC source)
- Inject vertically polarized electrons into the High Energy Ring (HER) - needs low enough emittance source to be able to inject.
- Rotate spin to longitudinal before IP, and then back to vertical after IP using solenoidal and dipole fields – recent studies have demonstrated feasibility
- Use Compton polarimeter to monitor longitudinal polarization with <1% absolute precision, higher for relative measurements (arXiv:1009.6178) - needed for real time polarimetry – similar to HERA and EIC technologies.
- Use tau decays to obtain absolute average polarization at IP – *BaBar* analysis demonstrates 0.5% precision (see C. Miller, Lake Louise Winter Institute 2022)

"Chiral Belle II" -> Left-Right Asymmetries

- Measure *difference* between cross-sections with left-handed beam electrons and right-handed beam electrons
- Same technique as SLD A_{LR} measurement at the Z-pole giving single most precise measurement of :

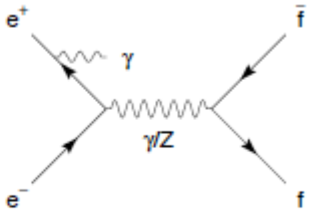
$$\sin^2\theta_{eff}^{lepton} = 0.23098 \pm 0.00026$$

- At 10.58 GeV, polarized e^- beam yields product of the neutral axial-vector coupling of the electron and vector coupling of the final-state fermion via Z-γ interference:

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle Pol \rangle$$

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

(for s-channel Born)

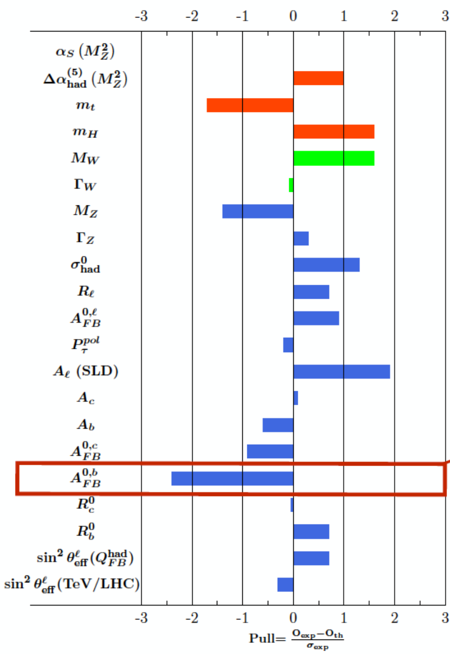


Belle II/SuperKEKB with a polarized e⁻ beam can address this long-standing electroweak discrepancy and hint of NP

Warning: Does not include CDF 2022 W mass update.

SM fit results: Predictions for EWPO

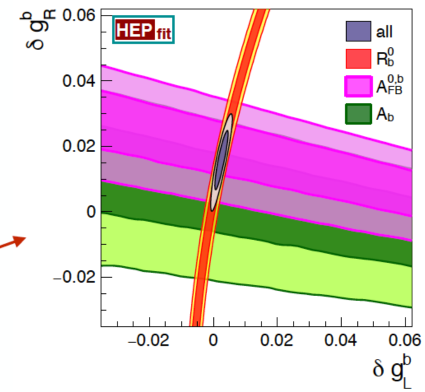
Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception



~2.5 σ discrepancy in forward-fackward asymmetry of the b quark

Requires modifications of (right-handed) *Zbb* couplings

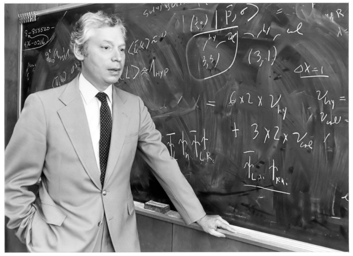
$$g_{L,R}^b = g_{L,R}^{b\,SM} + \delta g_{L,R}^b$$



	Fit result	Correlations	
δg_R^b	0.017±0.007	1.00	
δg_L^b	0.003±0.001	0.89	1.00

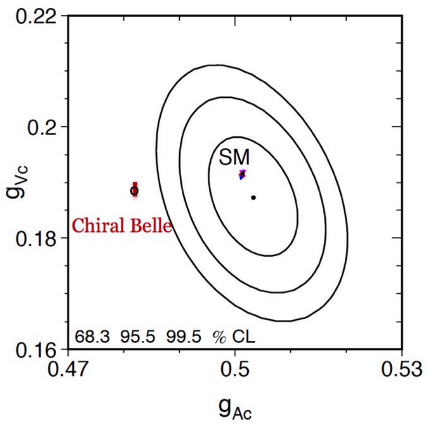
A New Path for Belle II Discovery in a *Precision Neutral Current Electroweak Program* with Heavy Quarks

- Left-Right Asymmetries (A_{LR}) yield high precision measurements of the *neutral current vector couplings* (g_V) to each of accessible fermion flavor, f :
  - beauty (D-type) (as well as for 3 charged leptons and light quarks)
  - charm (U-type)

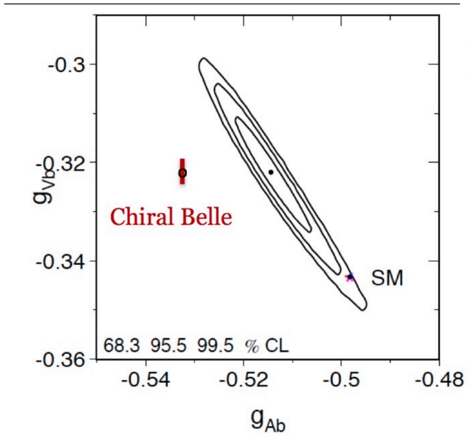


Steve Weinberg

c-quark:
Chiral Belle ~7 times more precise



b-quark:
Chiral Belle ~4 times more precise
with 20 ab^{-1}



$$\text{Recall: } g_V^f \text{ gives } \theta_W \text{ in SM} \begin{cases} g_A^f = T_3^f \\ g_V^f = T_3^f - 2Q_f \sin^2\theta_W \end{cases}$$

T_3 = -0.5 for charged leptons and D-type quarks
+0.5 for neutrinos and U-type quarks

Unique Access to New Physics in bottom-to-charm Neutral Current Vector Coupling Universality Ratio via A_{LR} (b-bbar)/ A_{LR} (c-cbar)

Belle II

Projections of b-quark and c-quark Neutral Current Vector Coupling Sensitivities with 70% polarized e^- beam

UNPRECEDENTED PRECISION

Final State Fermion	SM	World Average[1]	Chiral Belle 20 ab^{-1}	Chiral Belle 50 ab^{-1}	Chiral Belle 250 ab^{-1}
	g_V^f (M_Z)	g_V^f (M_Z)	$\sigma(g_V^f)$ or $\sigma(g_V^b/g_V^c)$	$\sigma(g_V^f)$ or $\sigma(g_V^b/g_V^c)$	$\sigma(g_V^f)$ or $\sigma(g_V^b/g_V^c)$
b-quark	-0.3437	-0.322	±0.0003(stat) ±0.0017(sys)	±0.0002(stat) ±0.0017(sys)	±0.00009(stat) ±0.0017(sys)
(eff.=0.3)	± .00049	±0.0077	±0.0017(total)	±0.0017(total)	±0.0017(total)
		2.8σ tension	**Improves x 4**	Improves x 4	Improves x 4
c-quark	0.192	0.1873	±0.0006(stat) ±0.0009(sys)	±0.00035(stat) ±0.0009(sys)	±0.00016(stat) ±0.0009(sys)
(eff.=0.3)	± .0002	±0.0070	±0.0011(total)	±0.0010(total)	±0.0009(total)
			Improves x 7	Improves x 7	Improves x 8
g_V^b/g_V^c	-1.7901	-1.719	±0.0058 (stat ~ total)	±0.0034 (stat ~ total)	±0.00015 (stat ~ total)
Ratio	± .0005	± .082	**Improve x 14**	**Improve x 24**	**Improve x 53**
Relative error:	0.18%	4.8%	**0.32%**	**0.19%**	**0.09%**

Get stuck at ~20 ab^{-1}

Use the ratio

bottom-to-charm UNIVERSALITY RATIO Beam Polarization (dominant systematic) cancels in the ratio

$\sin^2\Theta_W$ - all LEP+SLD measurements combined WA = 0.23153 ± 0.00016

$\sin^2\Theta_W$ - Chiral Belle combined leptons with 40 ab^{-1} have error ~current WA